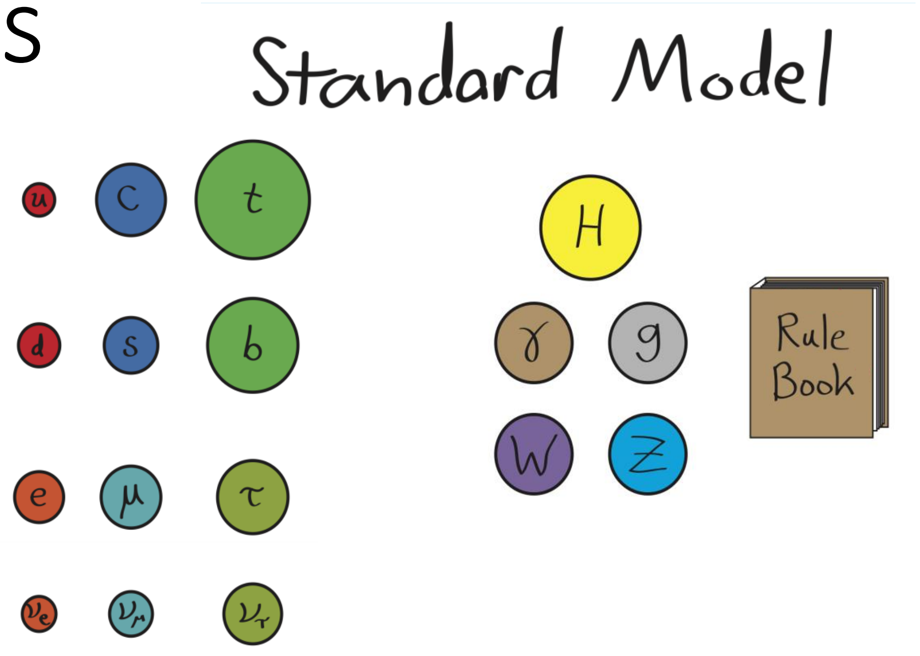
Twelve fold improved measurement of the electron's EDM with ThO

Cris Panda
ACME Collaboration
ECT Fundamental Symmetries
10/9/2018

EDMs probe TeV scale physics

- The Standard Model cannot explain
  - what is dark matter
  - baryogenesis - why is there more matter than antimatter



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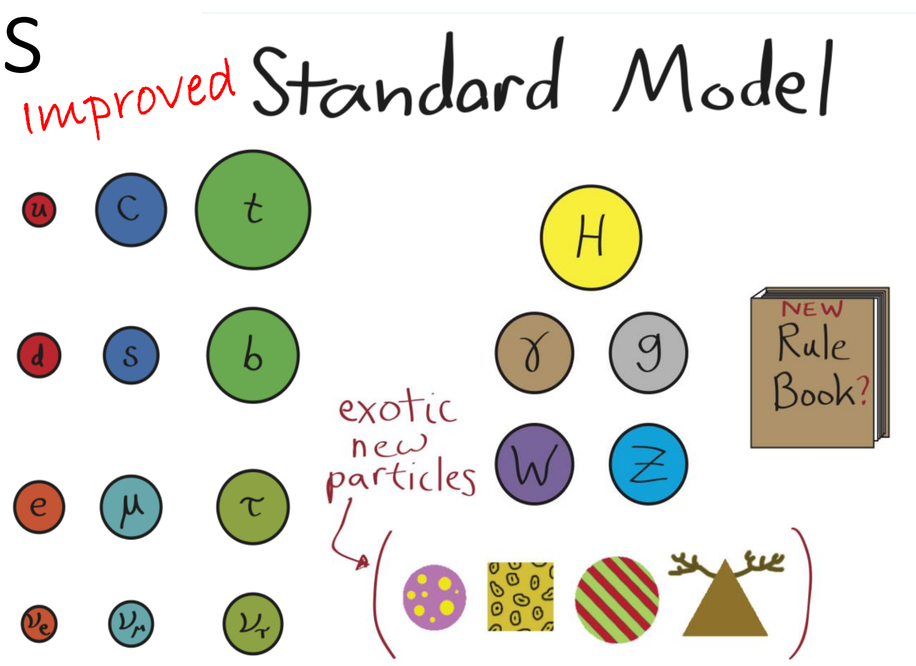

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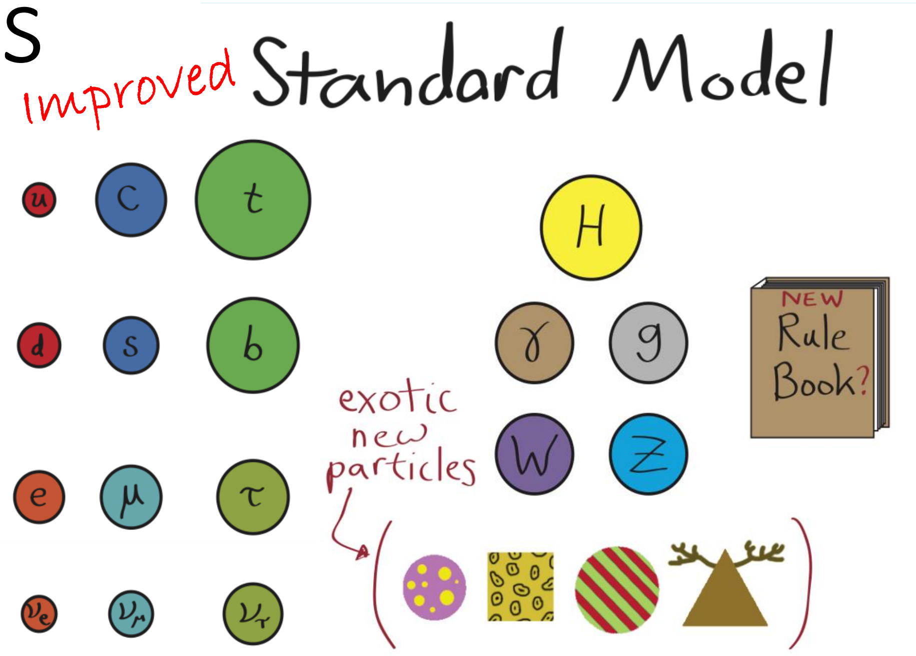
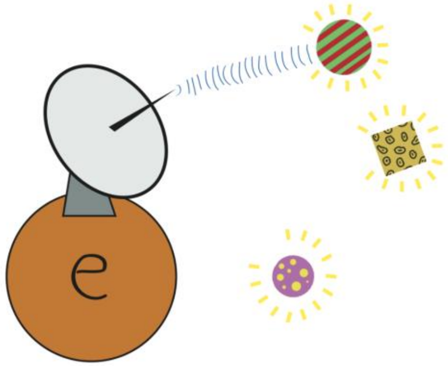
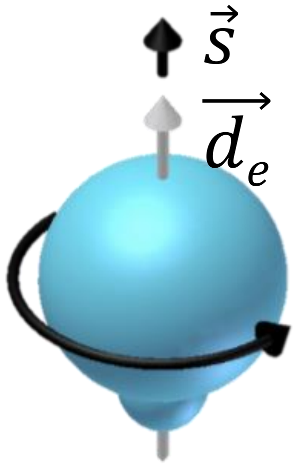


- The Standard Model cannot explain
  - what is dark matter
  - baryogenesis - why is there more matter than antimatter
- New theories predict particles at the TeV energy scale.
- Electron EDM sensitive to coupling with T-violating interactions with particles at the 3-30 TeV scale.
- No Standard Model

background.

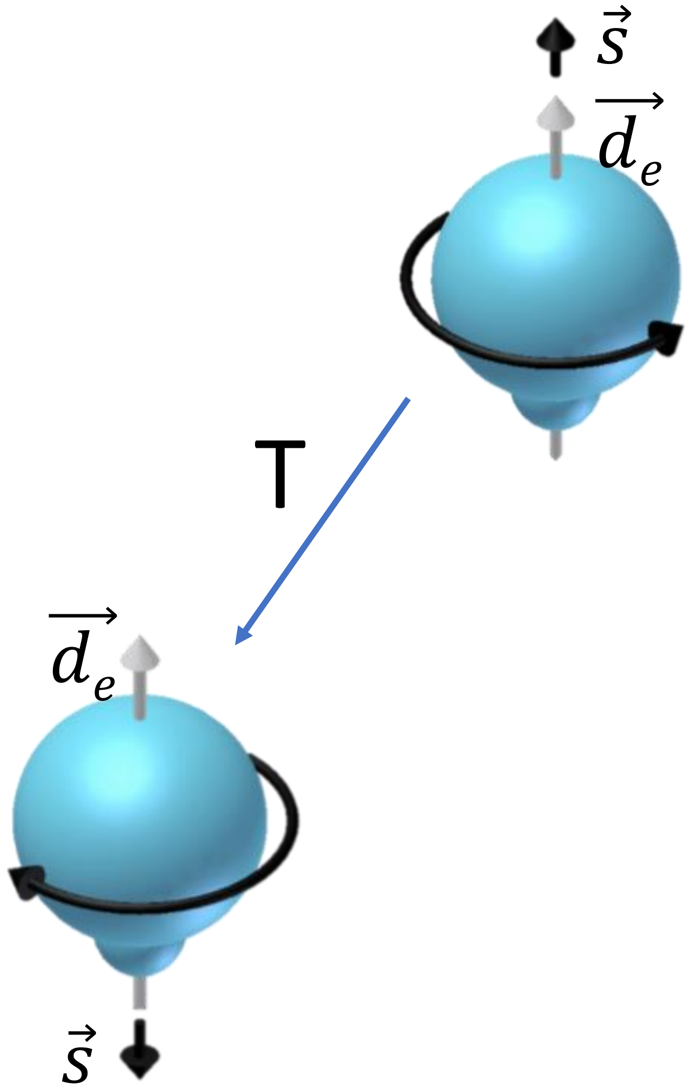


Electric dipole moments and fundamental symmetries



Electric dipole moments and fundamental symmetries

- Permanent EDMs of fundamental particles violate T-symmetry.



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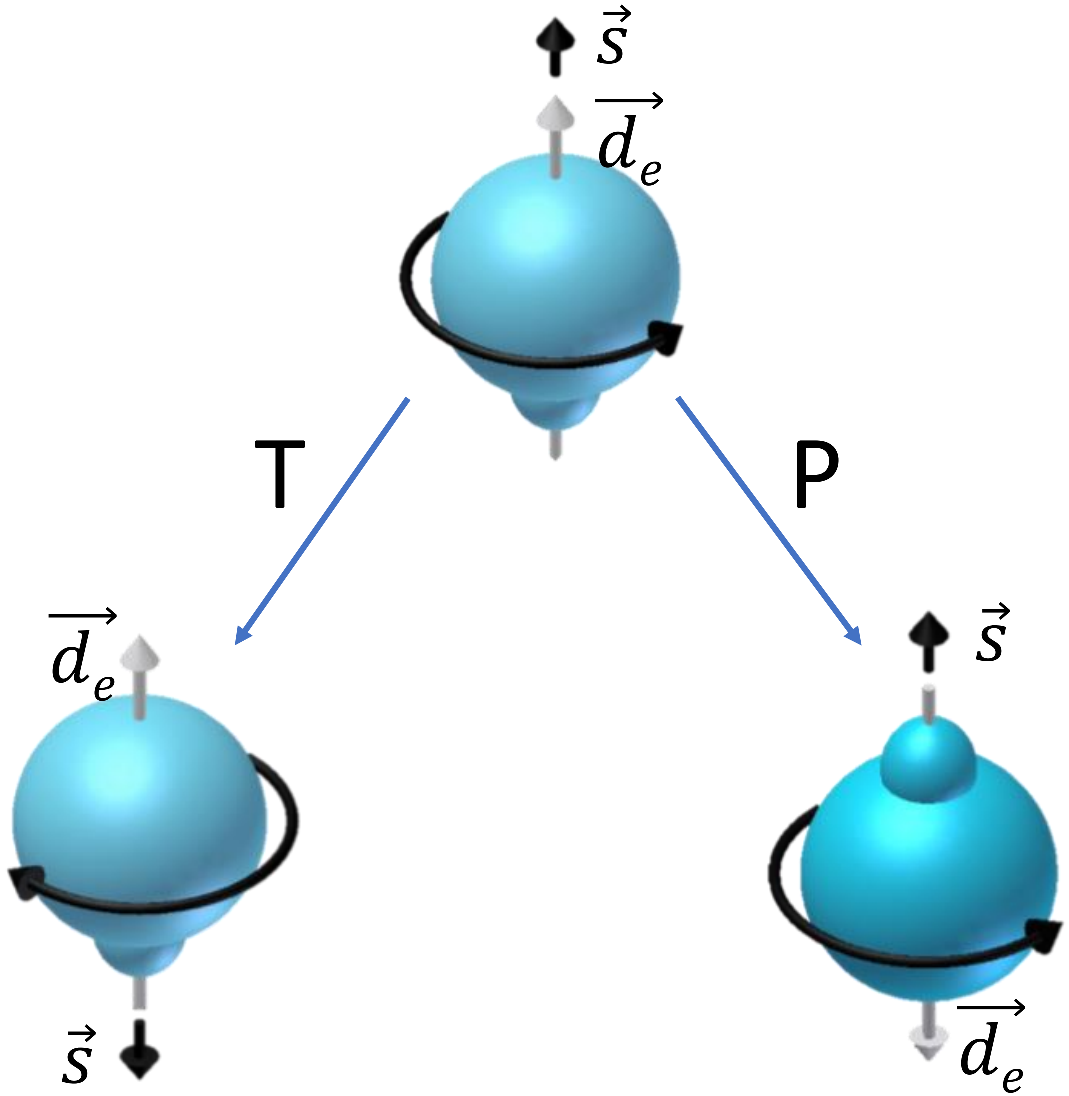
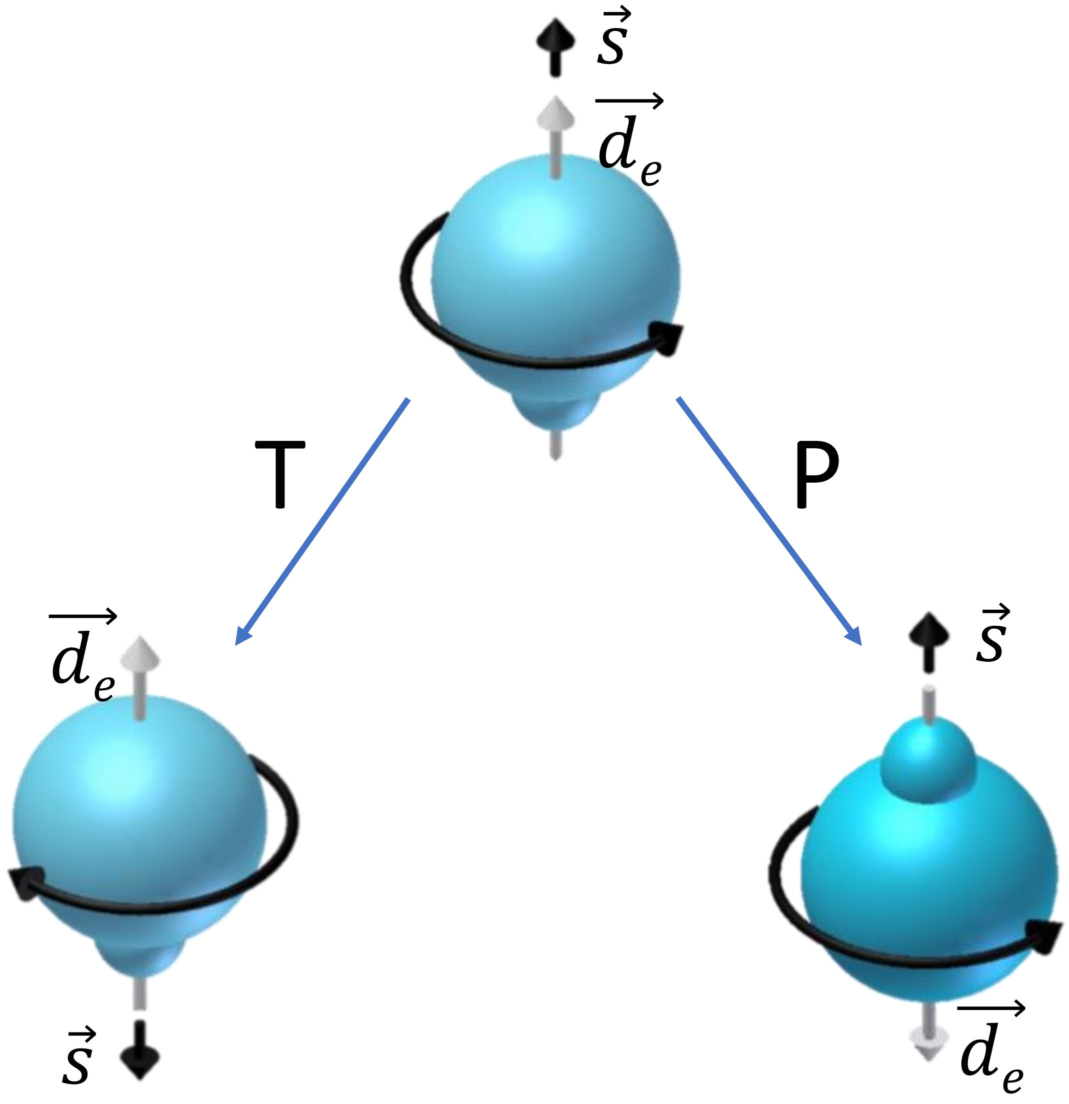


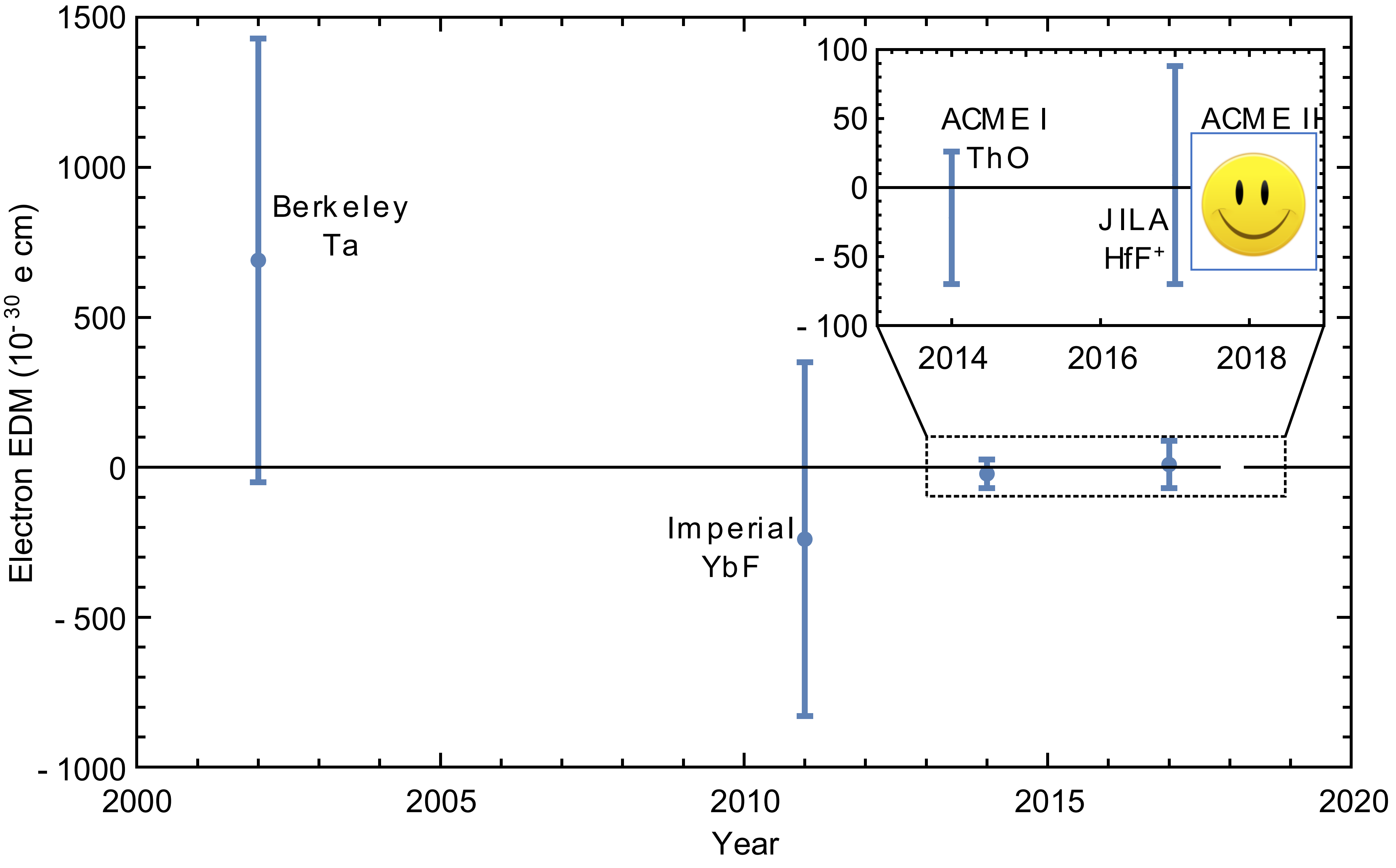
Electric dipole moments and fundamental symmetries

- Permanent EDMs of fundamental particles violate T-symmetry.
- EDMs are also not symmetric under parity inversion.
- CPT Theorem <-> EDMs are also CP-violating <-> baryogenesis.
- No permanent EDMs have yet been observed, despite 60 years of searching[1].



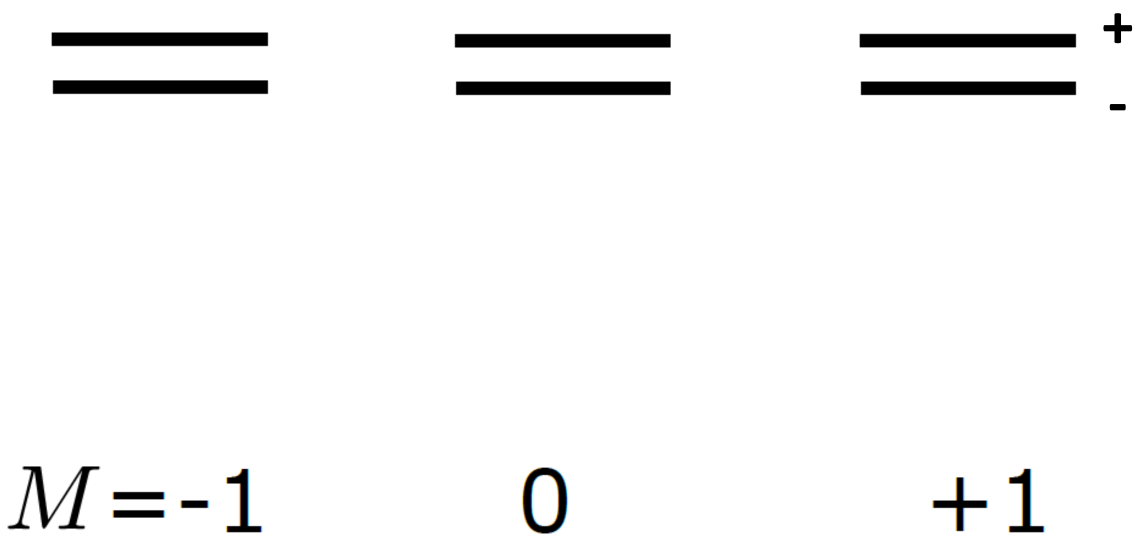
[1] Purcell, E. & Ramsey, N., *Phys. Rev.*, *78*(6), 807 (1950)

Electron EDM progress in this millennia



The Thorium Monoxide (ThO) $H\ ^3\Delta_1$ state

- High effective field.
- Can be easily polarized.
- Low magnetic noise sensitivity.



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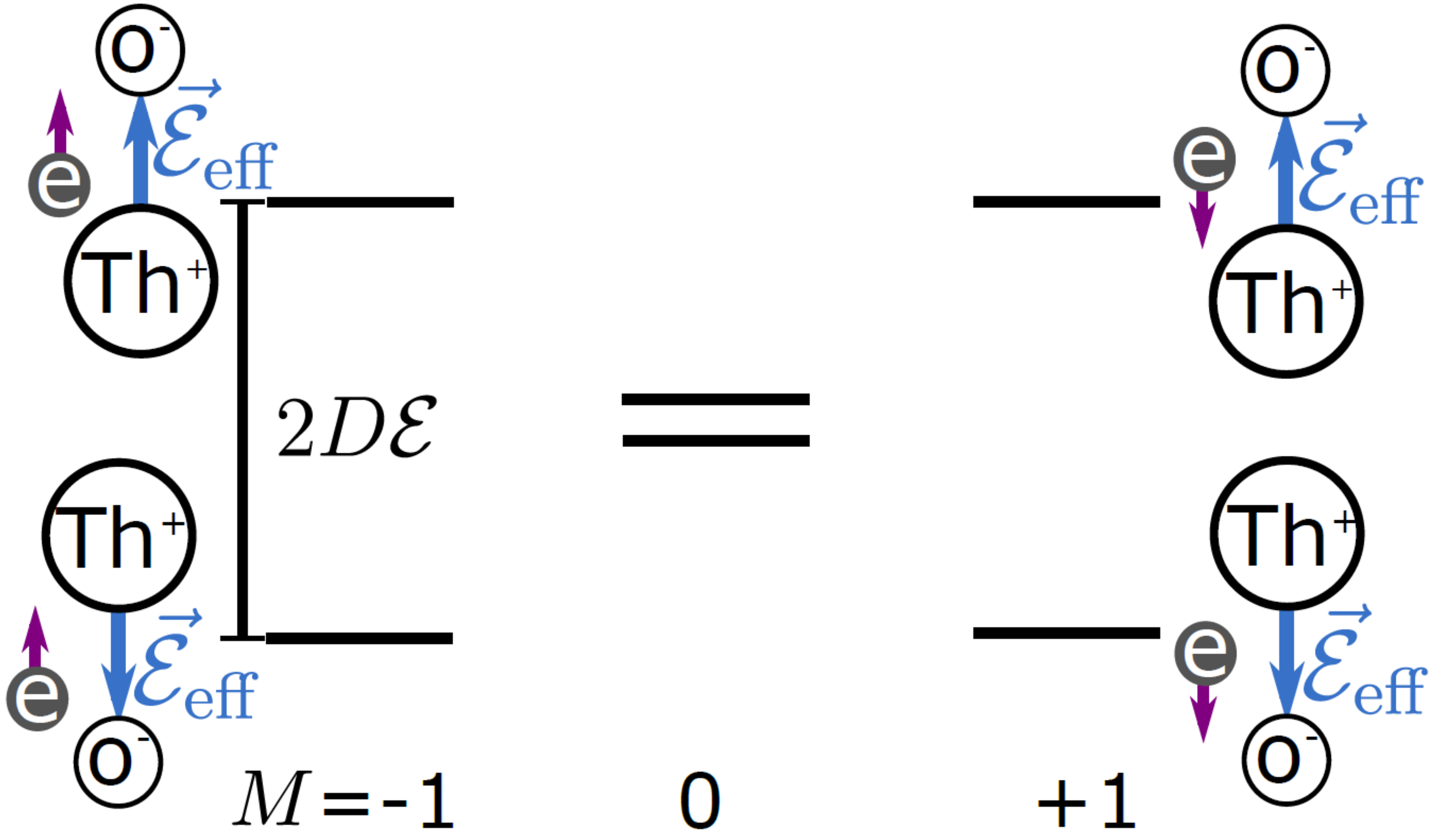

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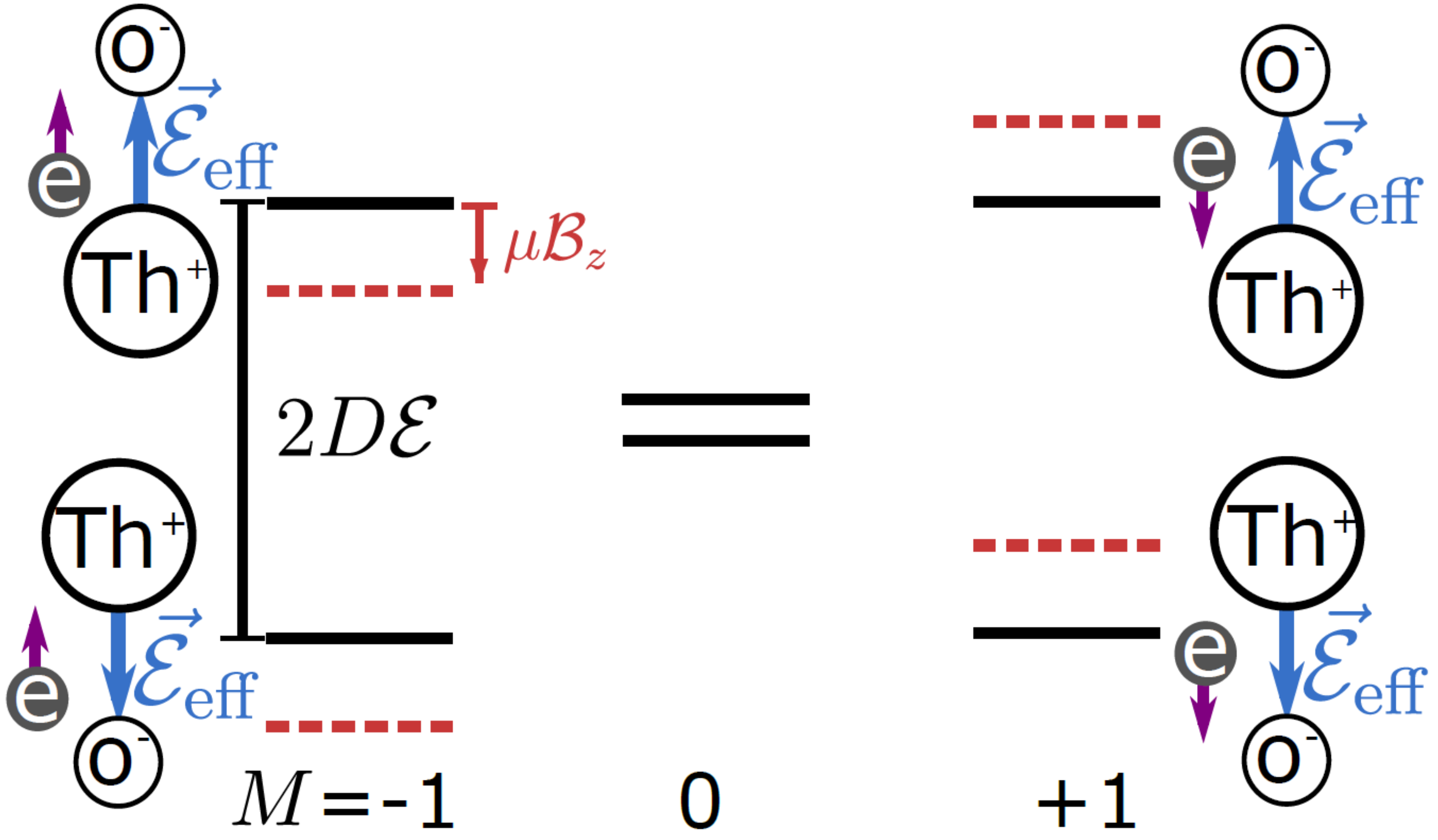

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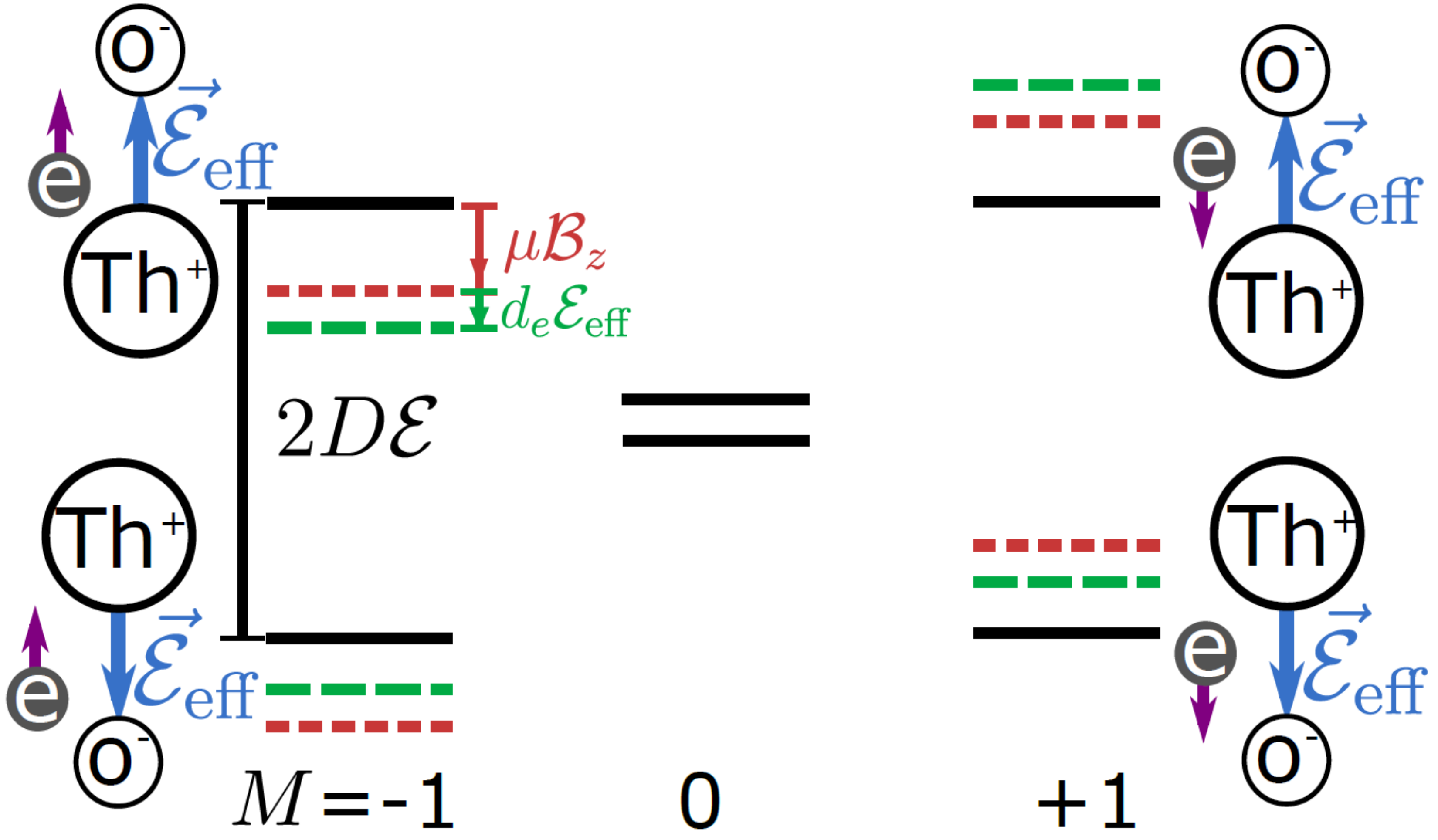

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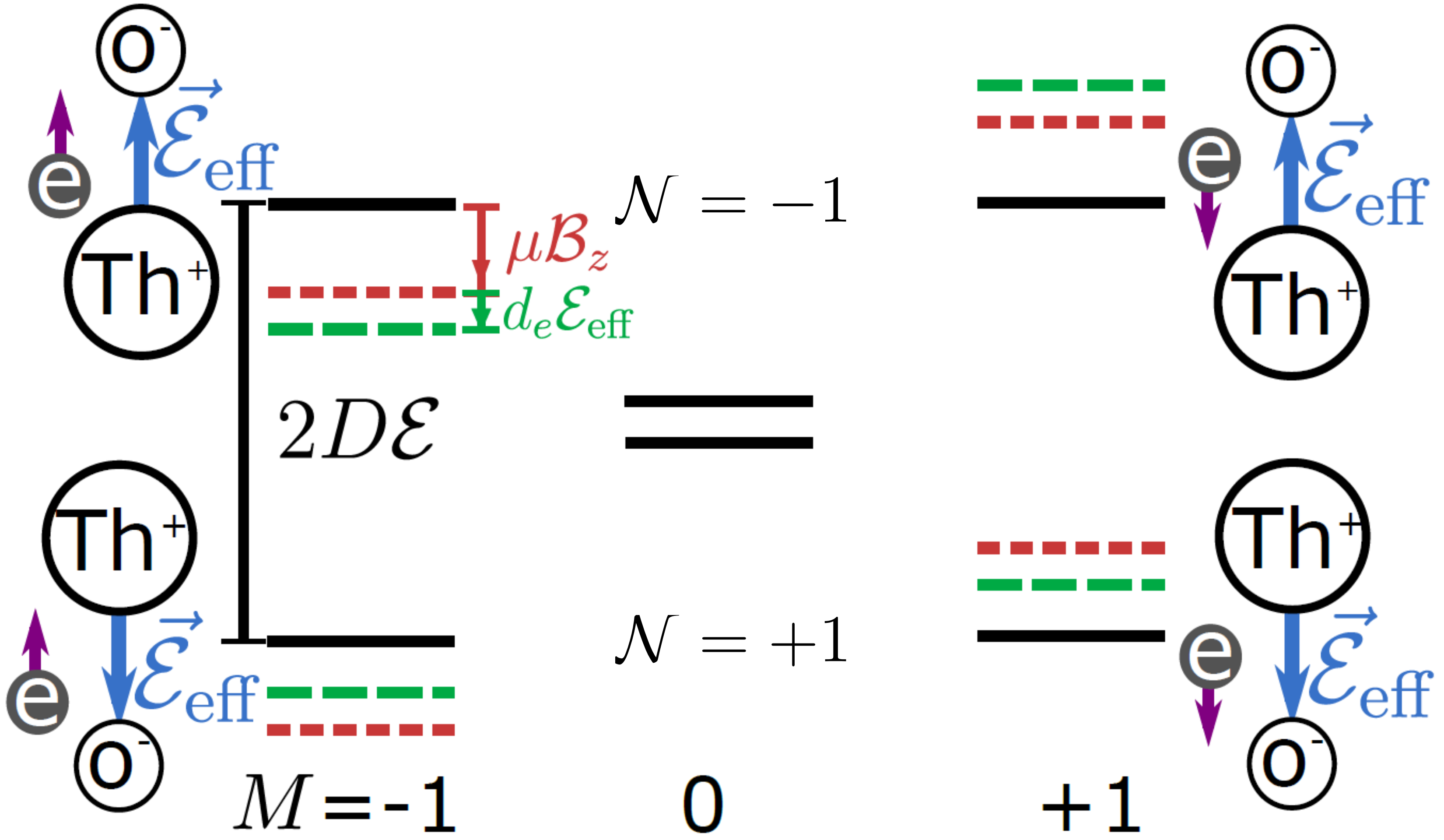
Can reverse the direction of $\vec{\mathcal{E}}_{\text{eff}}$ either by reversing:

- The lab electric field, E.
- The internal electric field, N.



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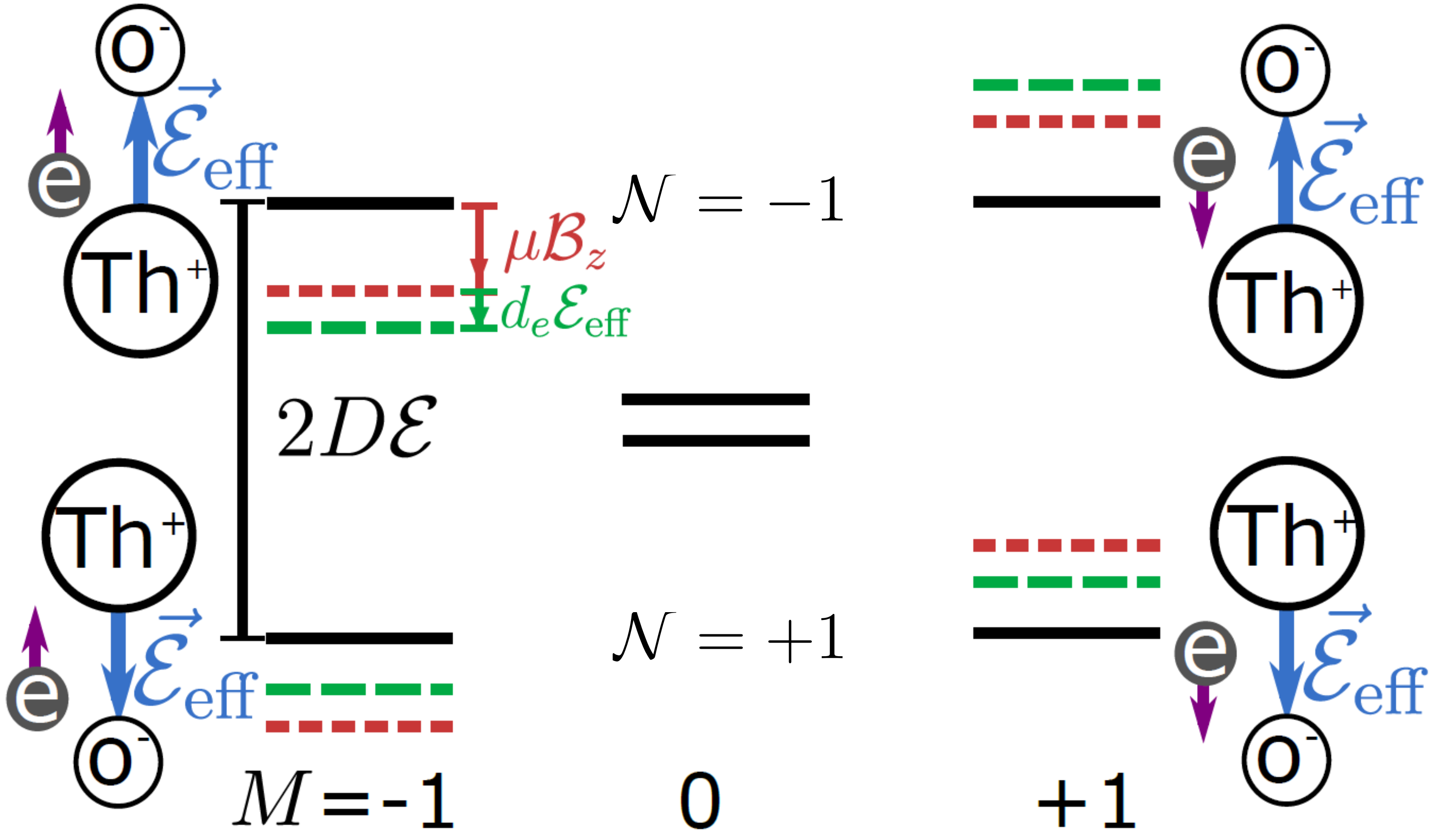
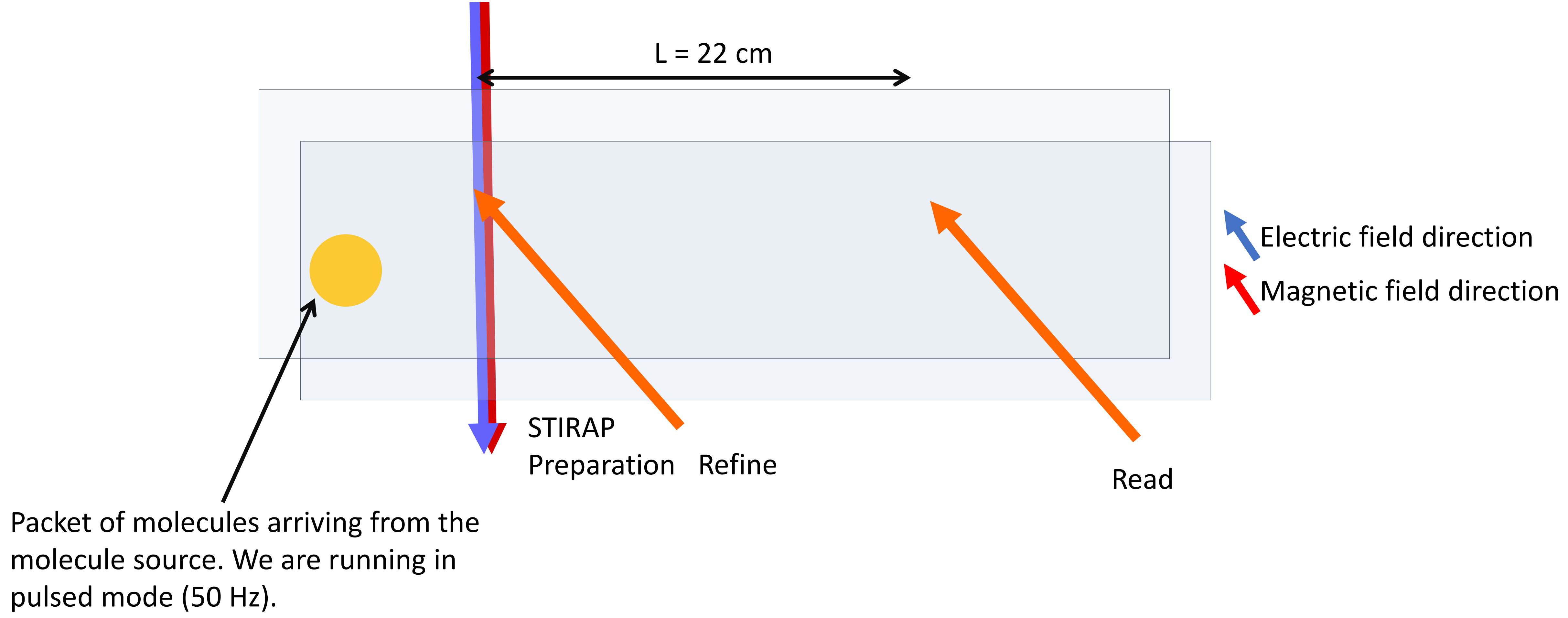
Measure EDM energy shift, NE correlated frequency $\omega^{\mathcal{N}\mathcal{E}}$.

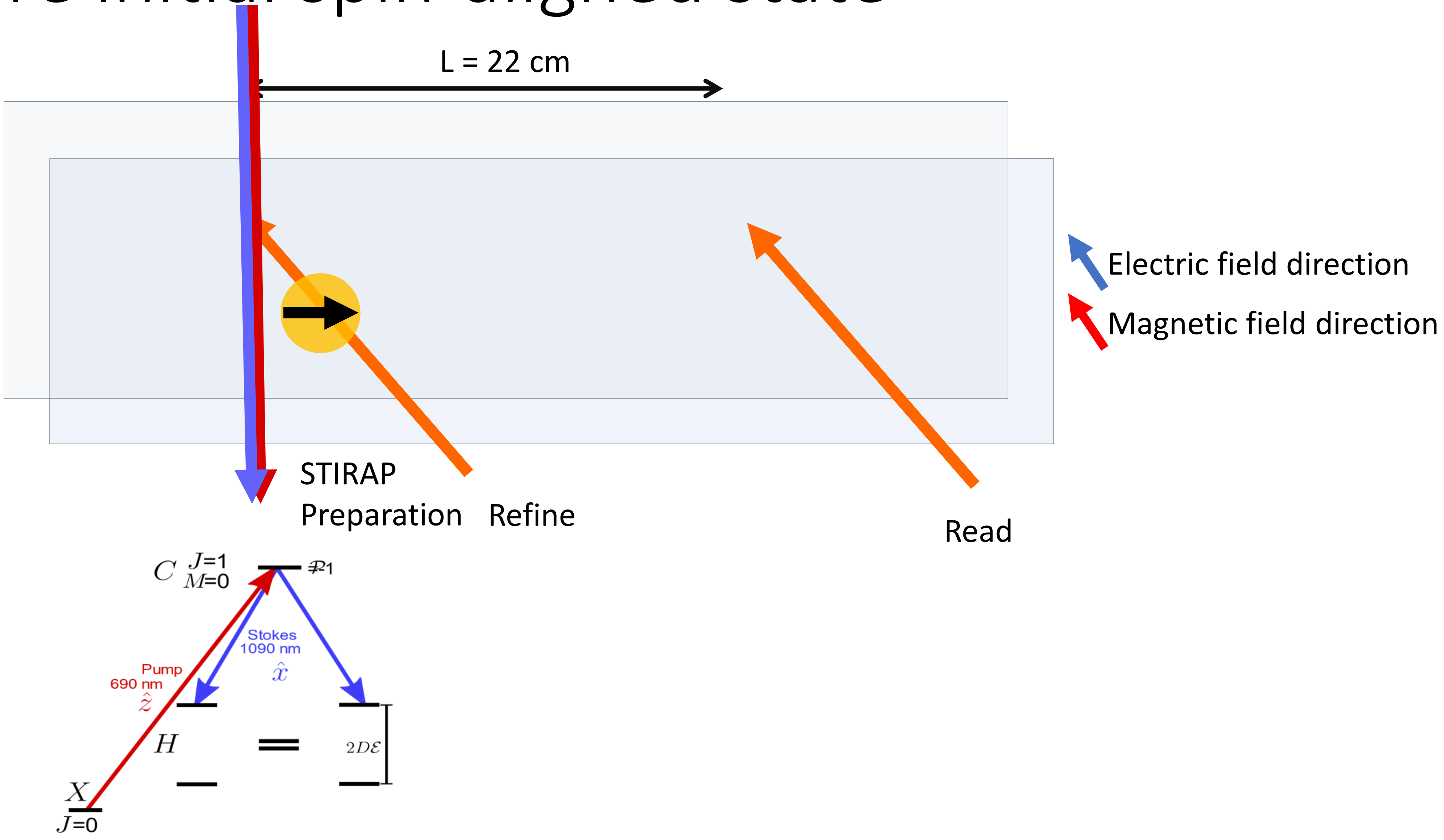
$$d_e \mathcal{E}_{\text{eff}} = -\hbar \omega^{\mathcal{N}\mathcal{E}}$$



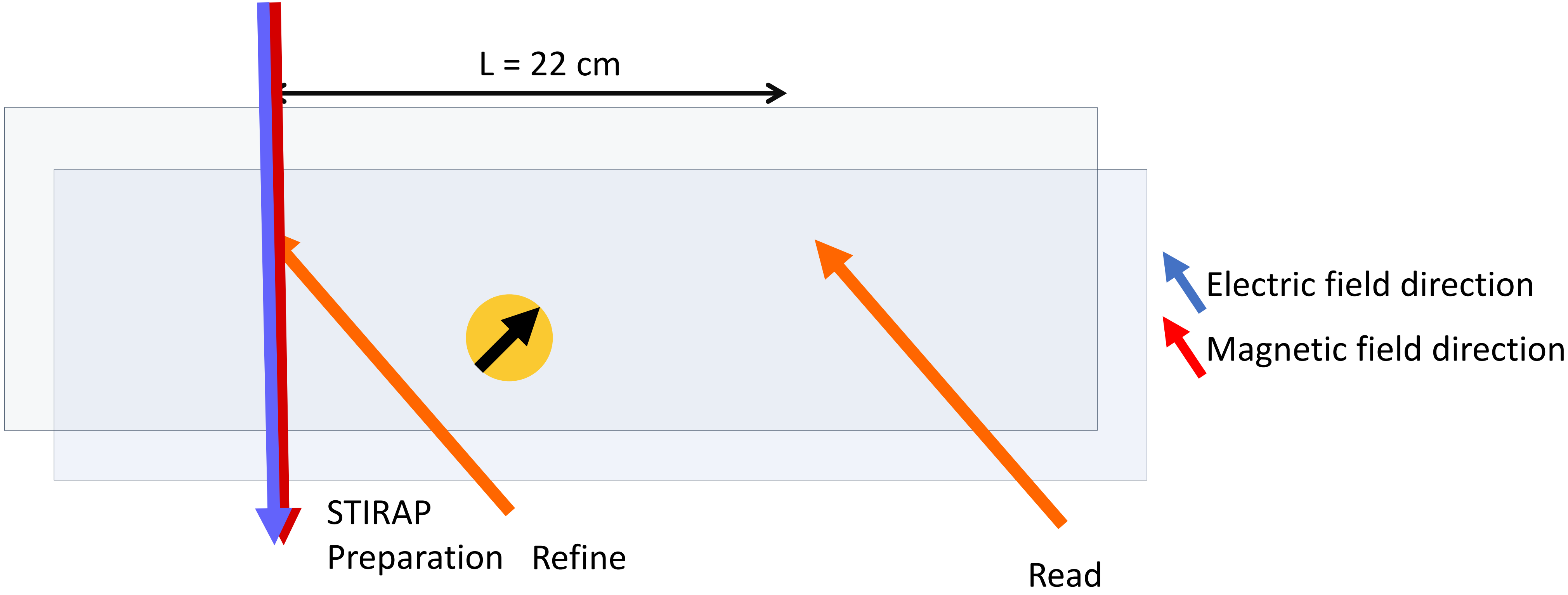
Phase measurement scheme

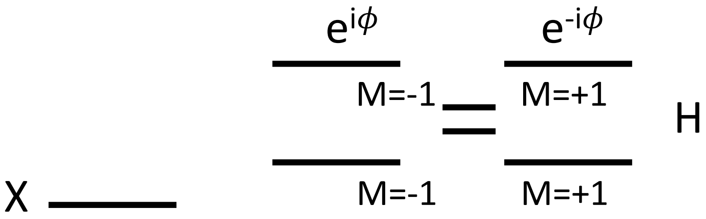


Prepare initial spin-aligned state

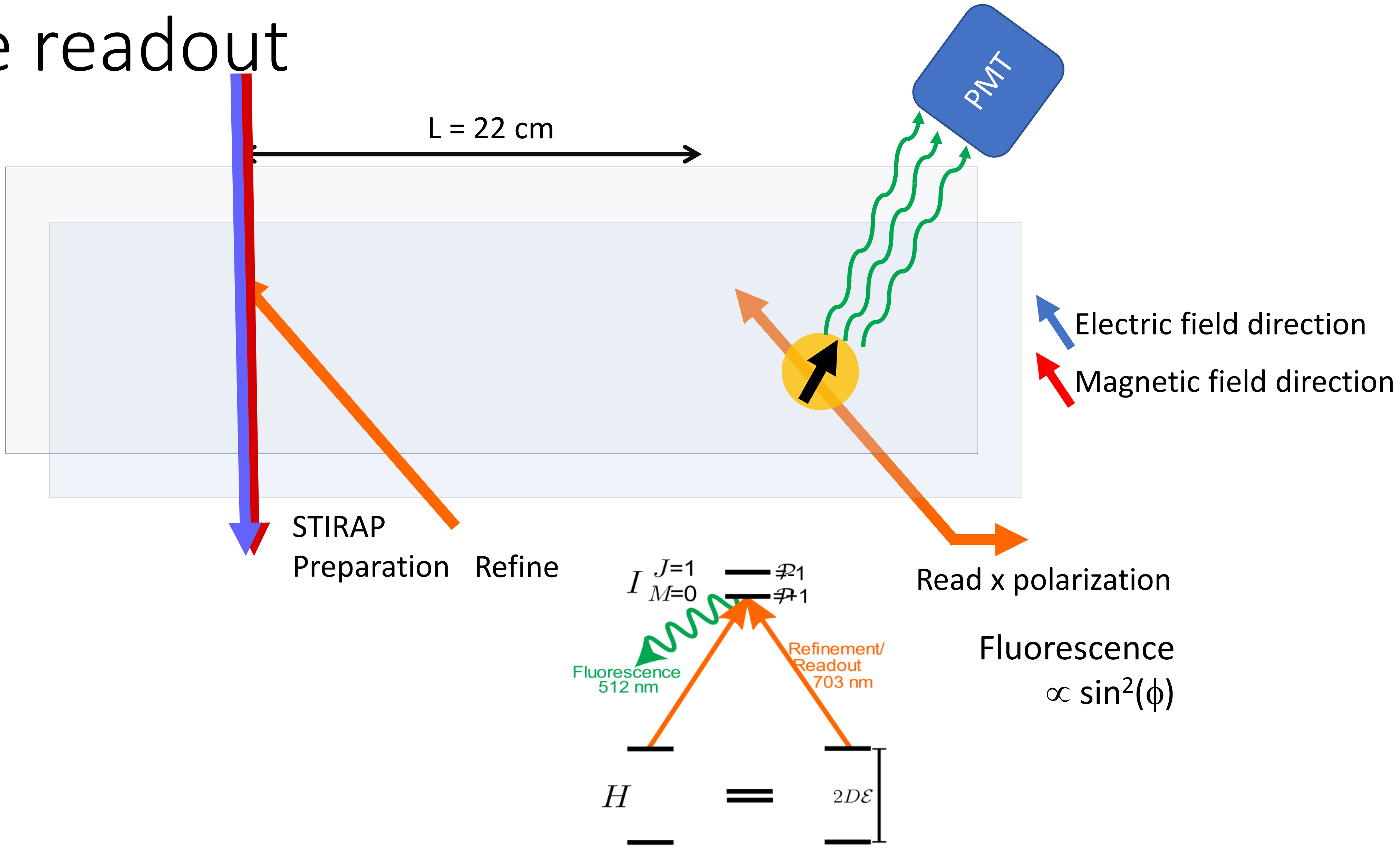


Spin Precession





Phase readout



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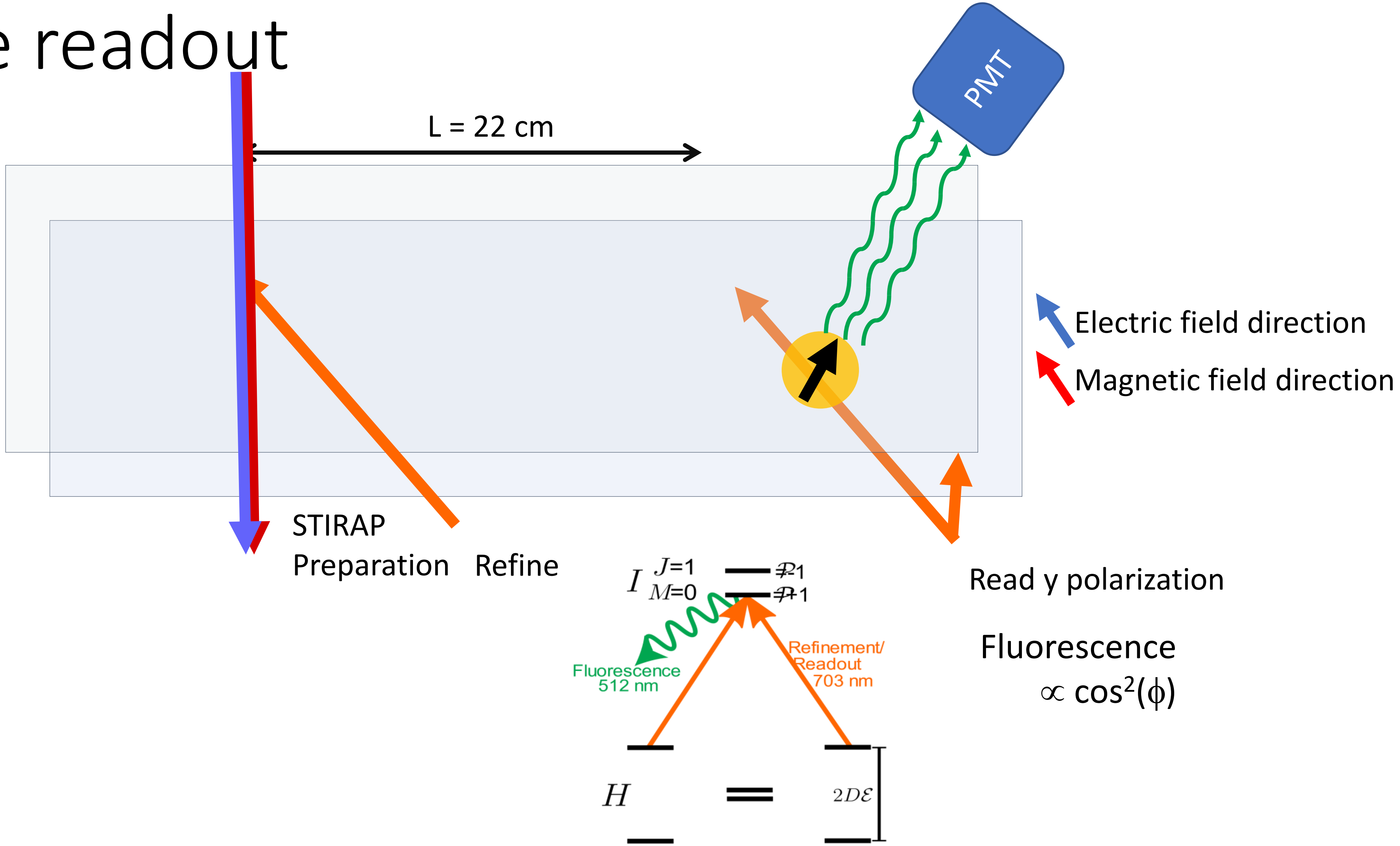
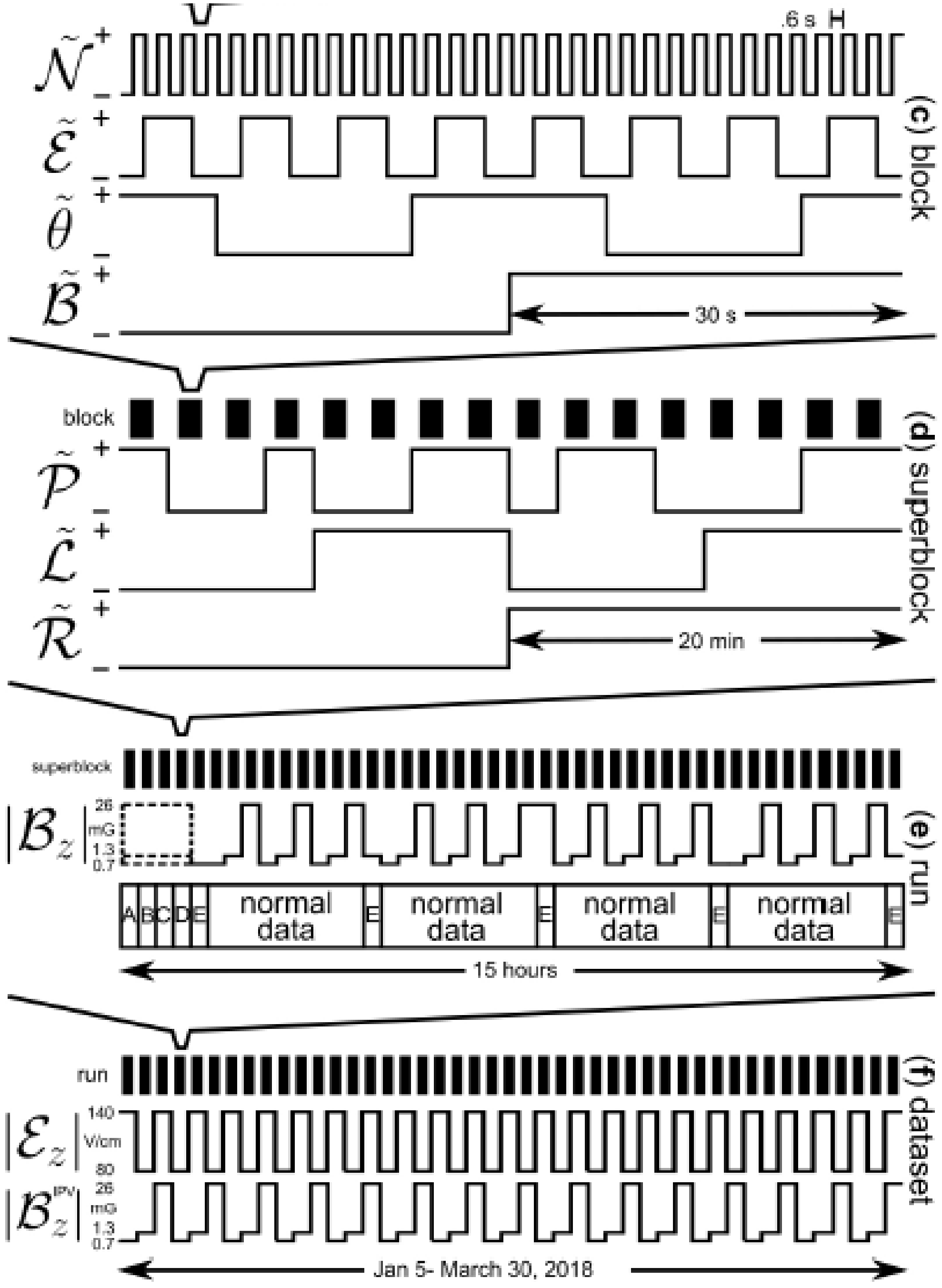


Switches

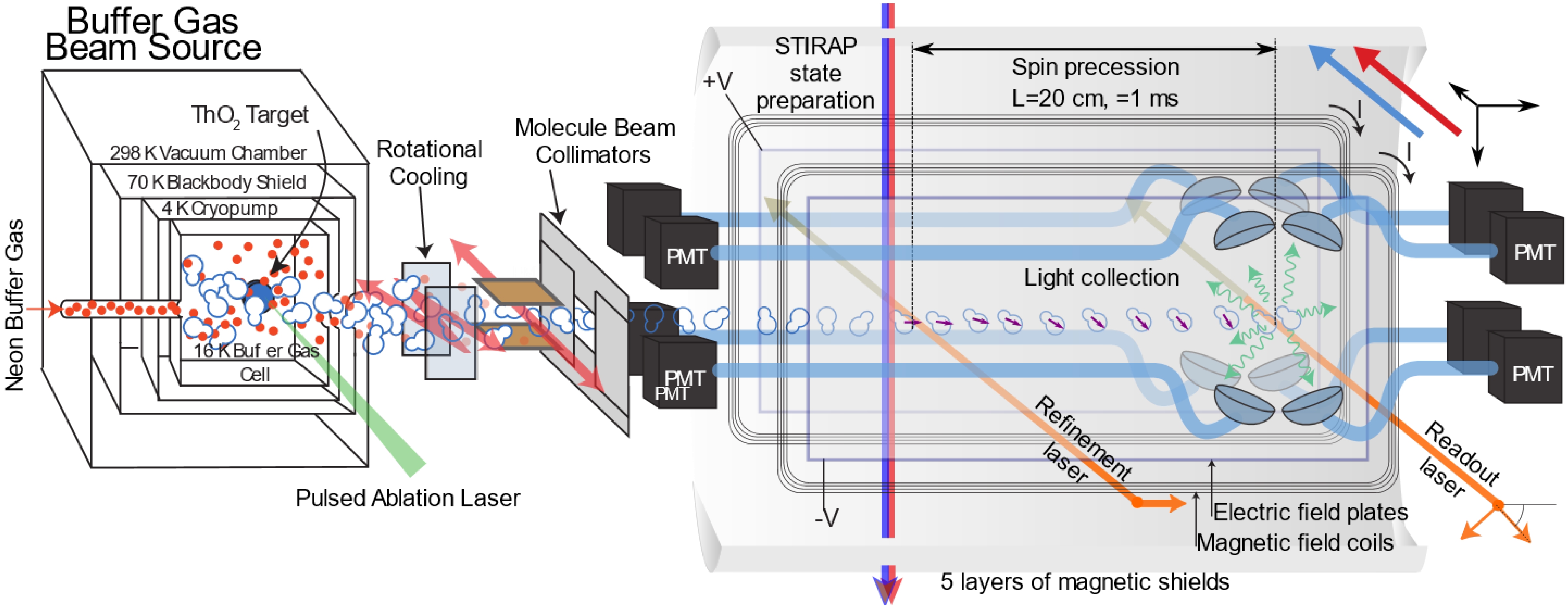
- EDM is correlated with N,E

$$d_e \mathcal{E}_{\text{eff}} = -\hbar\omega^{\mathcal{N}\mathcal{E}}$$

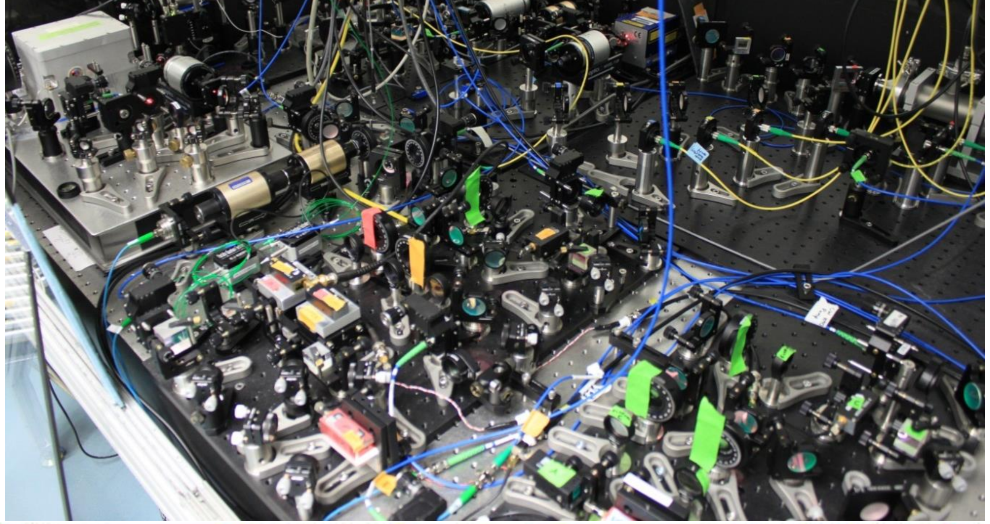
- More switches reject noise and systematic effects, P, L, R.
- In addition, monitor systematics during the dataset.
- Change magnitude of electric, magnetic field.

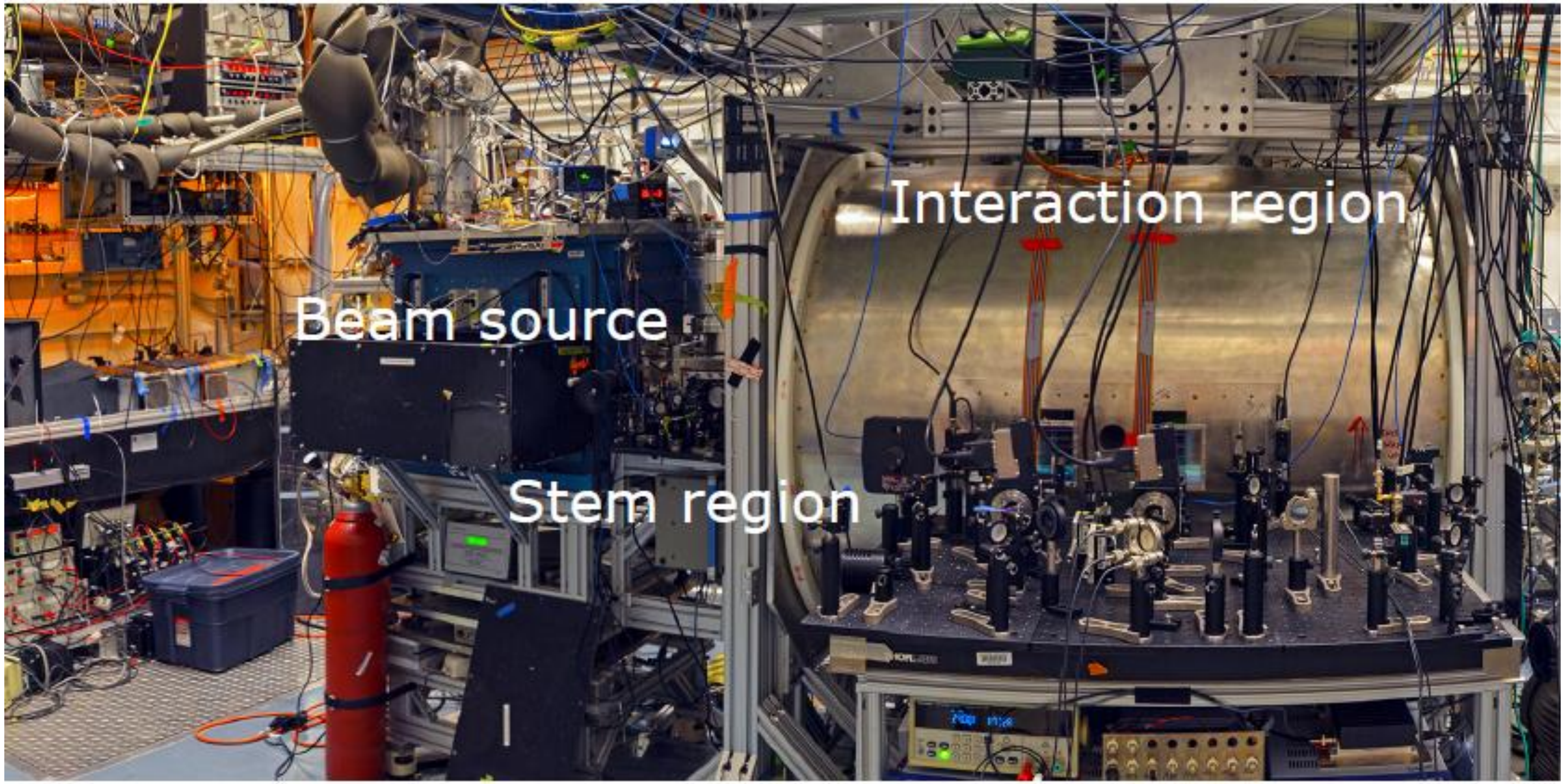


Schematic of ACME II Measurement

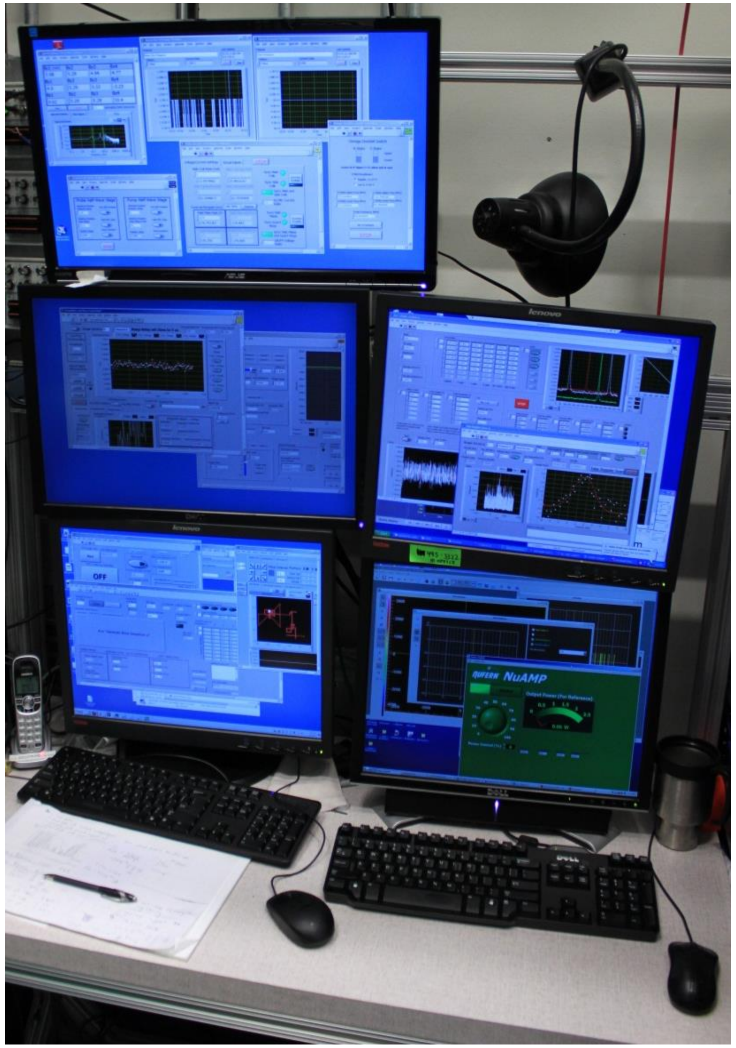


Real ACME II

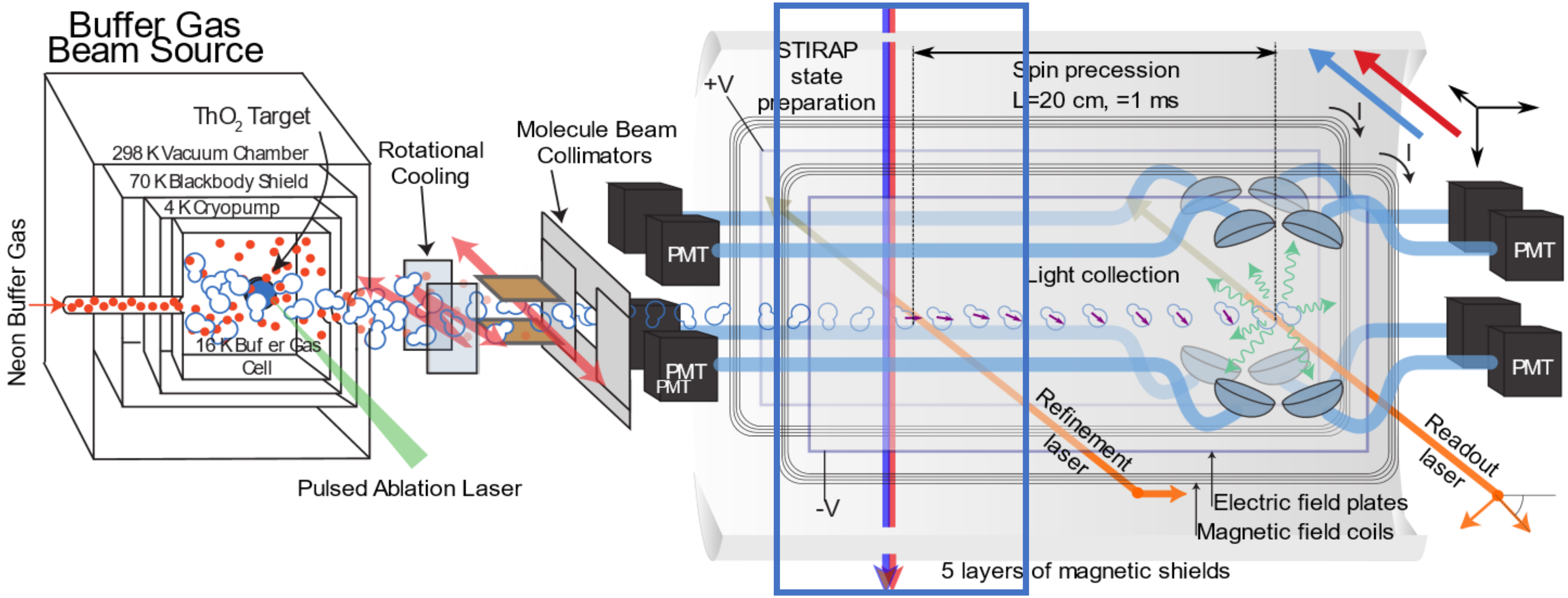




“control room”



ACME II, ~400x more signal



Improved signal through:

- Improved state preparation x12.

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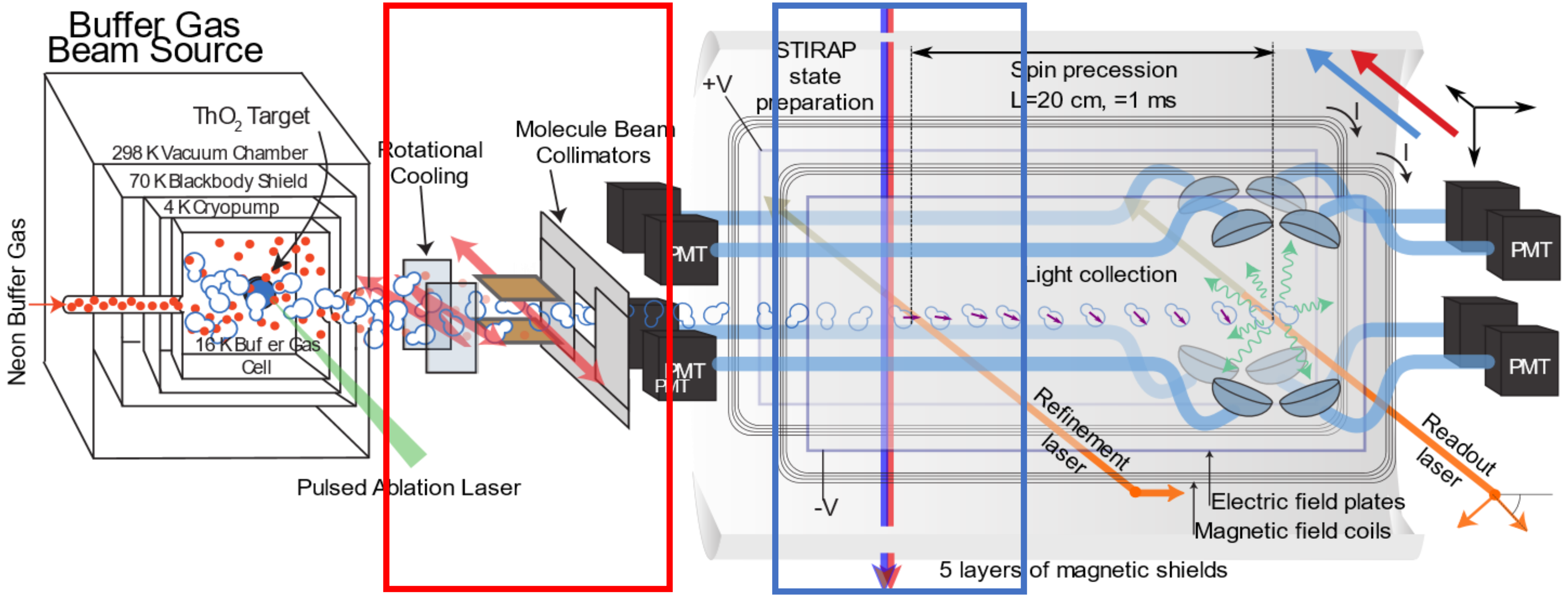

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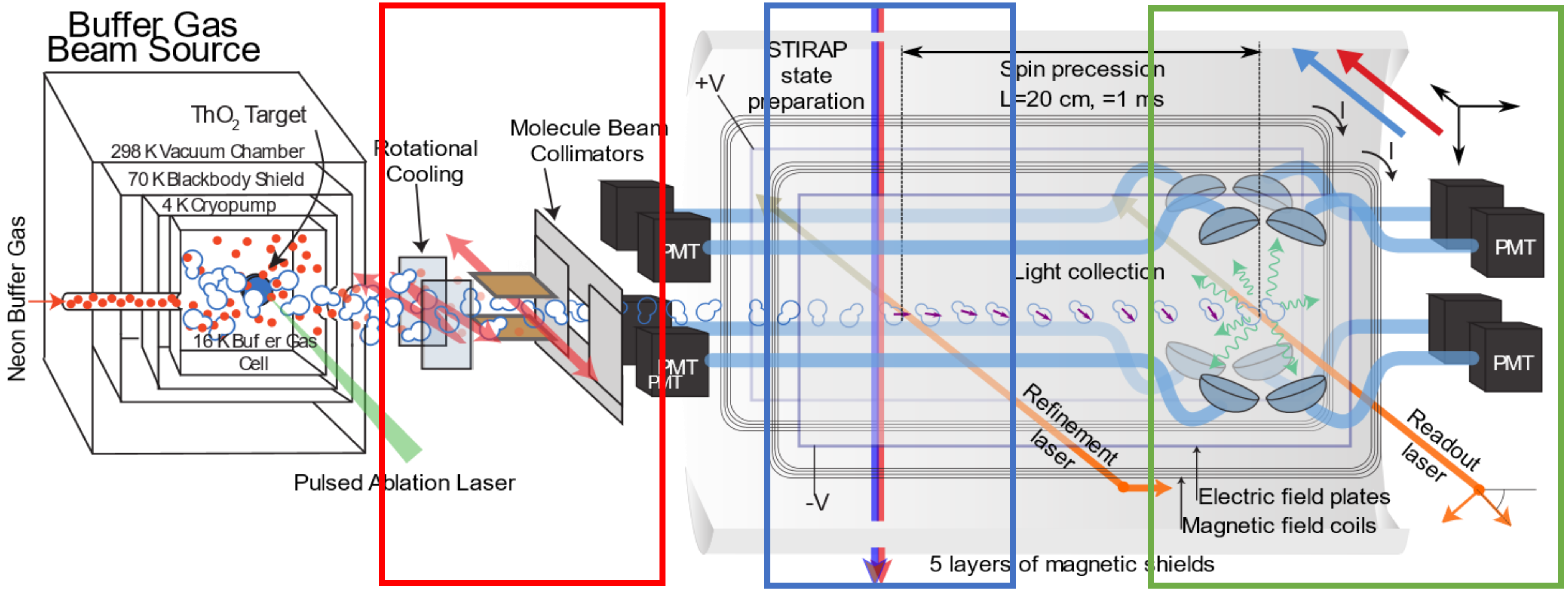

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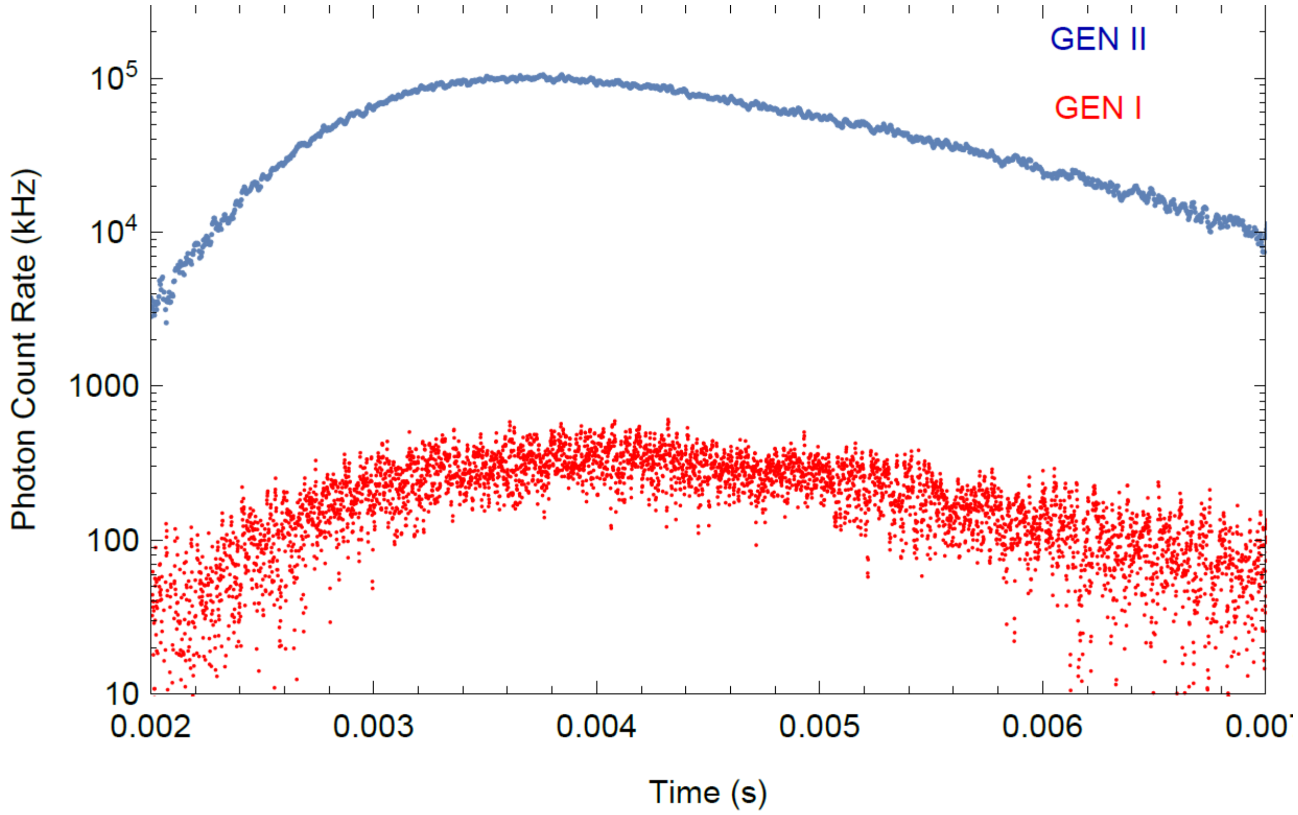

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Systematic effects

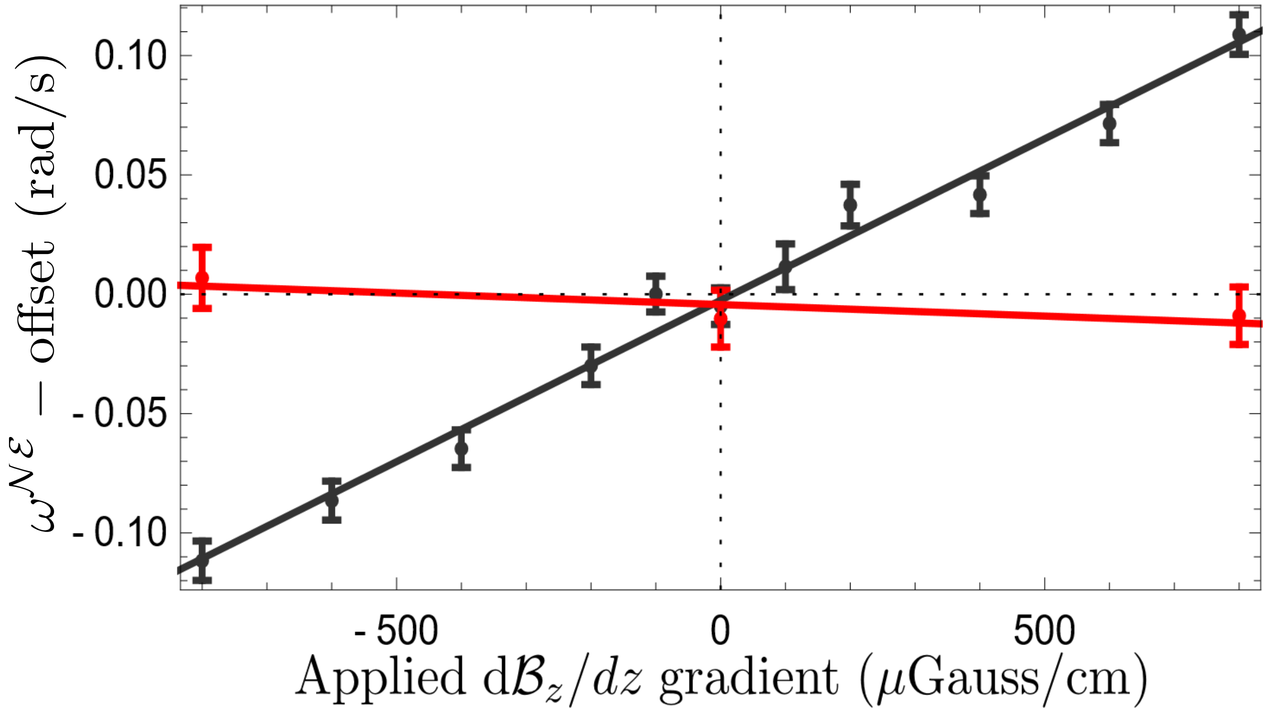
- Look for dependence of ω^{NE} on over 40 varied parameters.

Blue: limited range of IPV (<10x)
Yellow: larger range of IPV (>10x)
* part of systematic error bar

Systematic category	Systematic check	Units
Lasers: Pointing and position	Probe: applied pointing	mrad
	Cleanup: applied pointing	mrad
	Cleanup: position	mm
Lasers: Detuning	Cleanup detuning*	MHz
	Delta P	MHz
	Ti Sapph detuning (both cleanup a	MHz
	Delta N*	MHz
Lasers: Power	Low probe power	unitless (fraction of typ
	X,Y beams power asymmetry	unitless (Px-Py)/(Px+I
	I state power asymmetry	unitless (Plp-Plm)/(Plp
Lasers: Polarization	Cleanup ellipticity	S/I
	Probe ellipticity	S/I
	Probe polarization rotation	deg of lambda/2
Electric Field	E_mag large	V/cm
	E_mag small	V/cm
	Floating field plates*	V
Magnetic Field: Offsets	Bz_nr*	mGauss
	Bx_rev	mGauss
	By_rev	mGauss
	Bx_nr*	mGauss
	By_nr*	mGauss
Magnetic Field: Gradients	dBx/dx_nr*	mGauss/cm
	dBy/dy_nr*	mGauss/cm
	dBy/dz_nr*	mGauss/cm
	dBy/dx_nr*	mGauss/cm
	dBz/dx_nr*	mGauss/cm
	dBx/dx_rev	mGauss/cm
	dBy/dx_rev	mGauss/cm
	dBy/dy_rev	mGauss/cm
	dBy/dz_rev	mGauss/cm
	dBz/dx_rev	mGauss/cm
	dBz/dz_rev	mGauss/cm
DAQ parameters	Block switches settling times	fraction of typical
	Polarization switching frequency	kHz
	Waveplate dither angle	degrees of pol rotation

Systematic effects

- Look for dependence of ω^{NE} on over 40 varied parameters.
- Observed a shift of EDM frequency (ω^{NE}) with large applied dB_z/dz.



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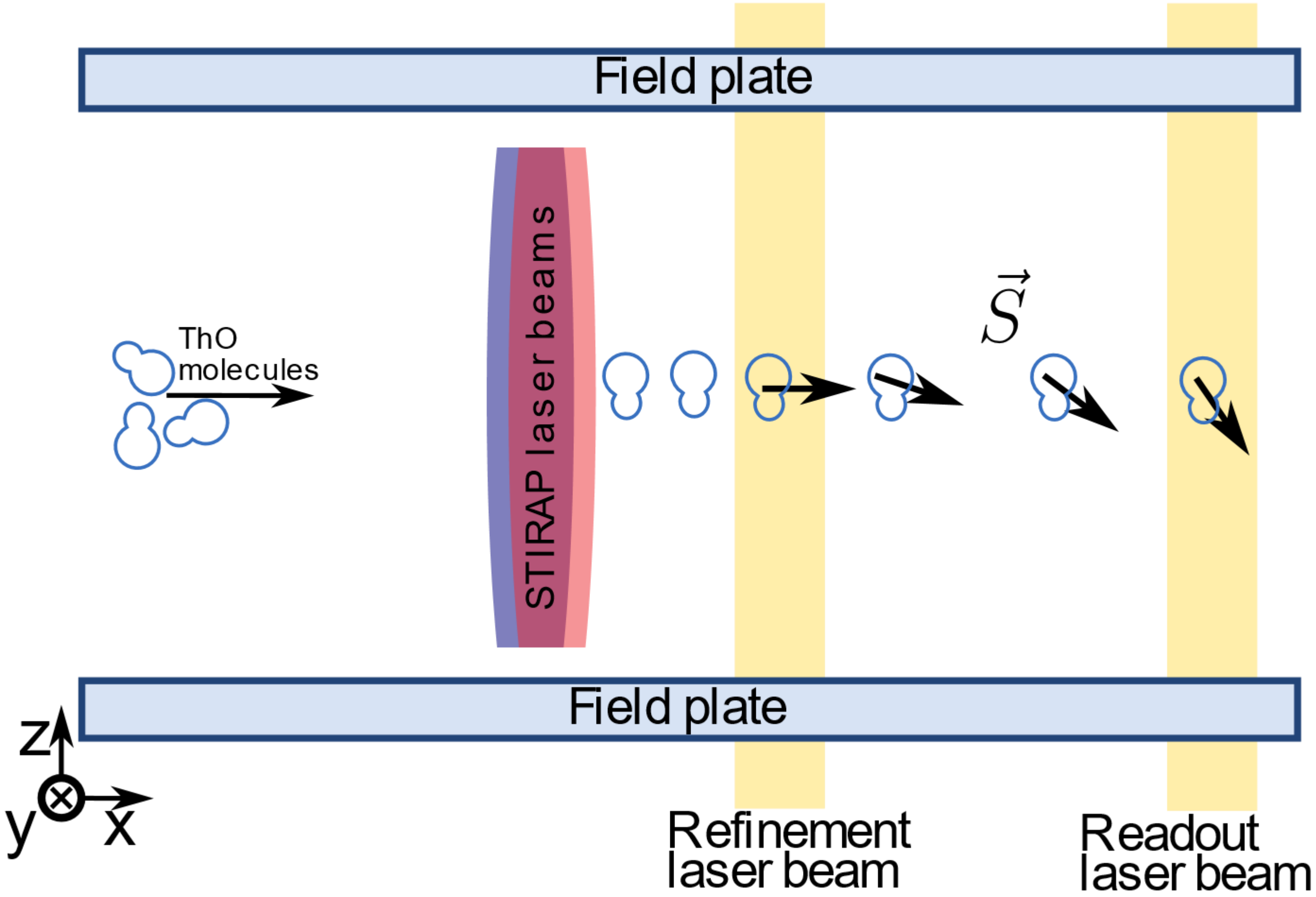
An Example Systematic: $dB_z/dz \times \delta \times dE^{nr}/dz$

- Typical molecule precession.



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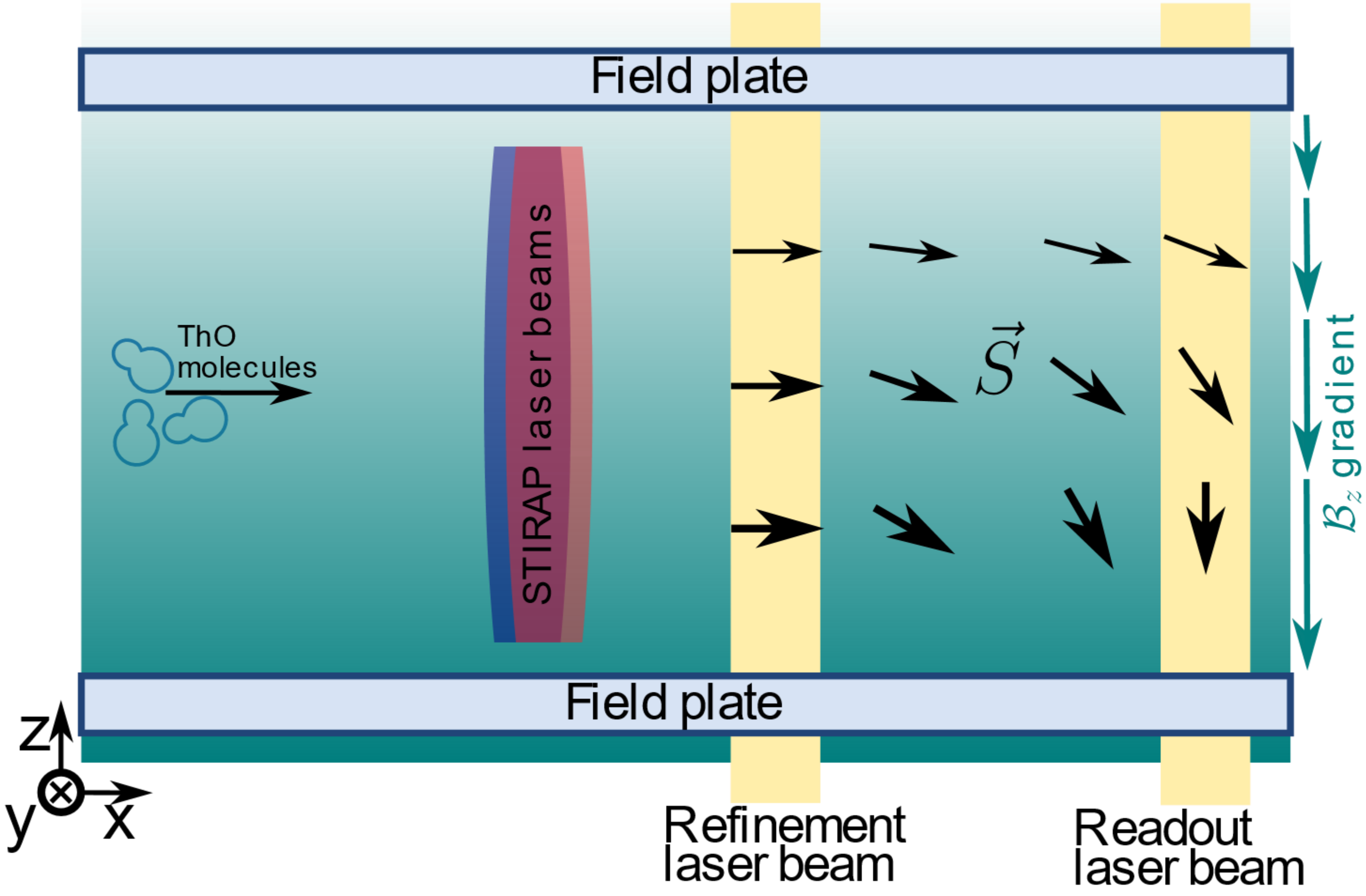
- In a dBz/dz gradient, molecules precess with different amounts depending on their z position.



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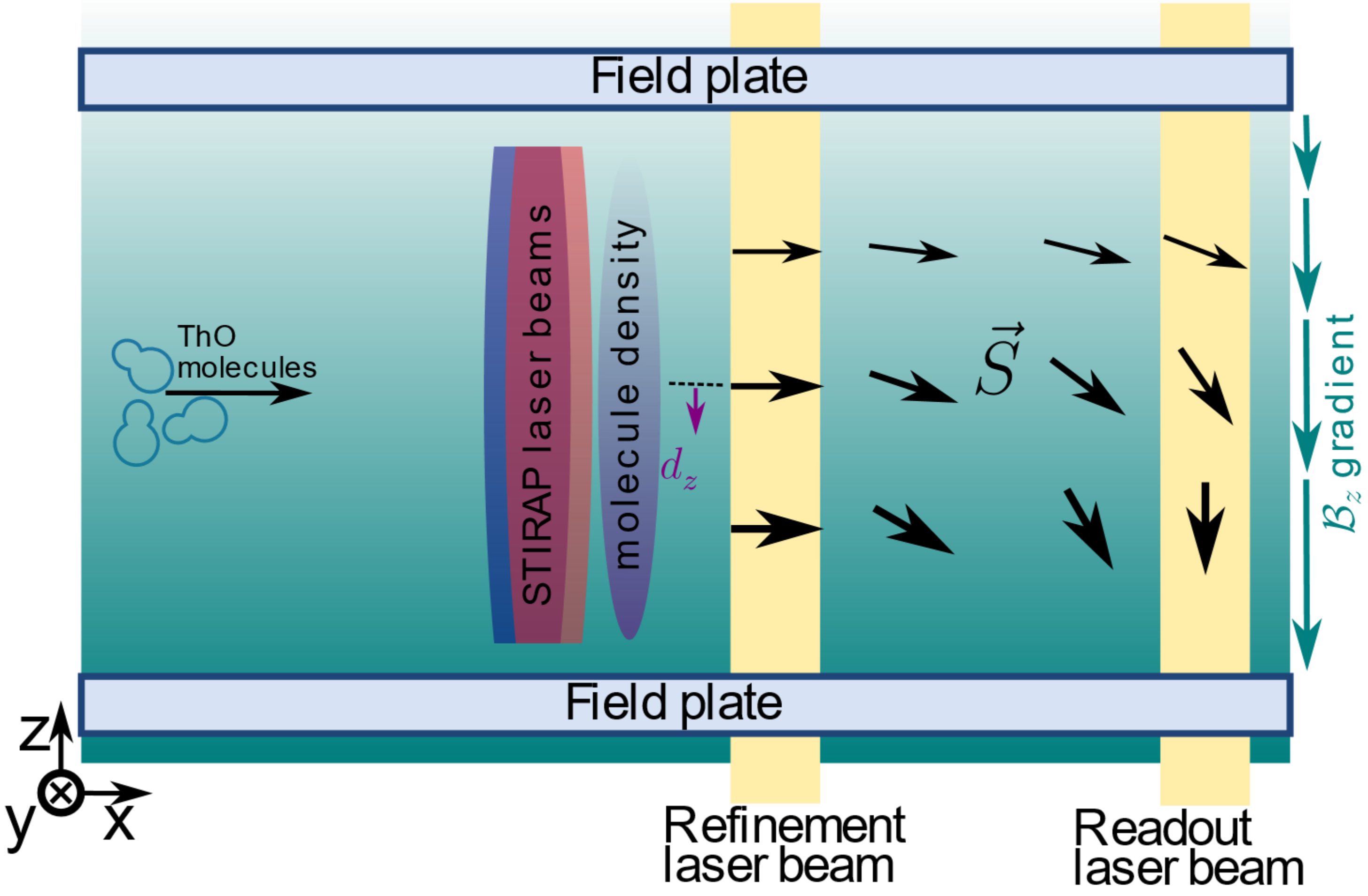
- A translation along z of the “center of mass”, dz, of the molecules can then cause a change in measured phase.



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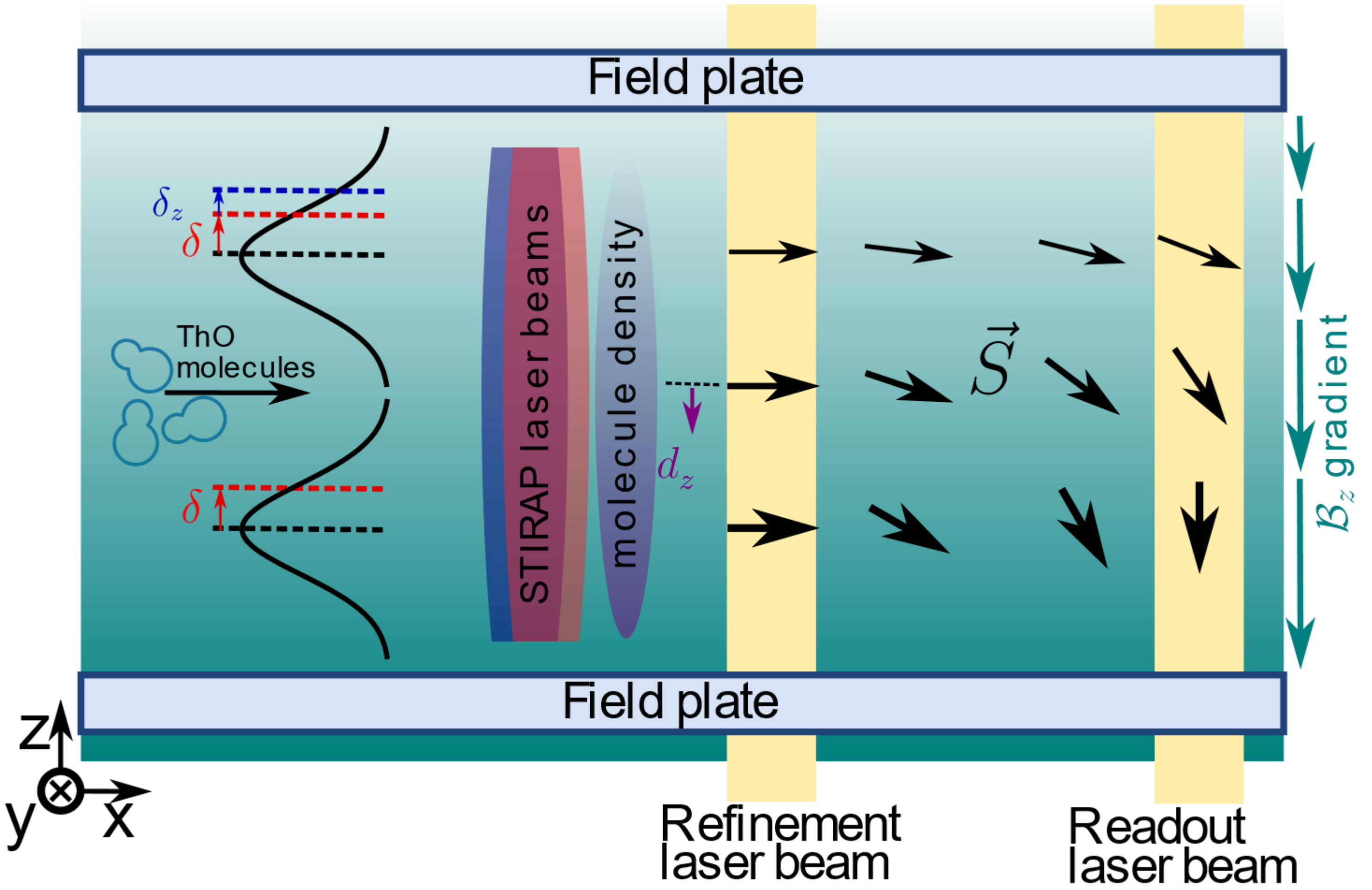
- Such a translation can occur due to a z-dependent state preparation efficiency, from a detuning δ_z of the STIRAP resonance.



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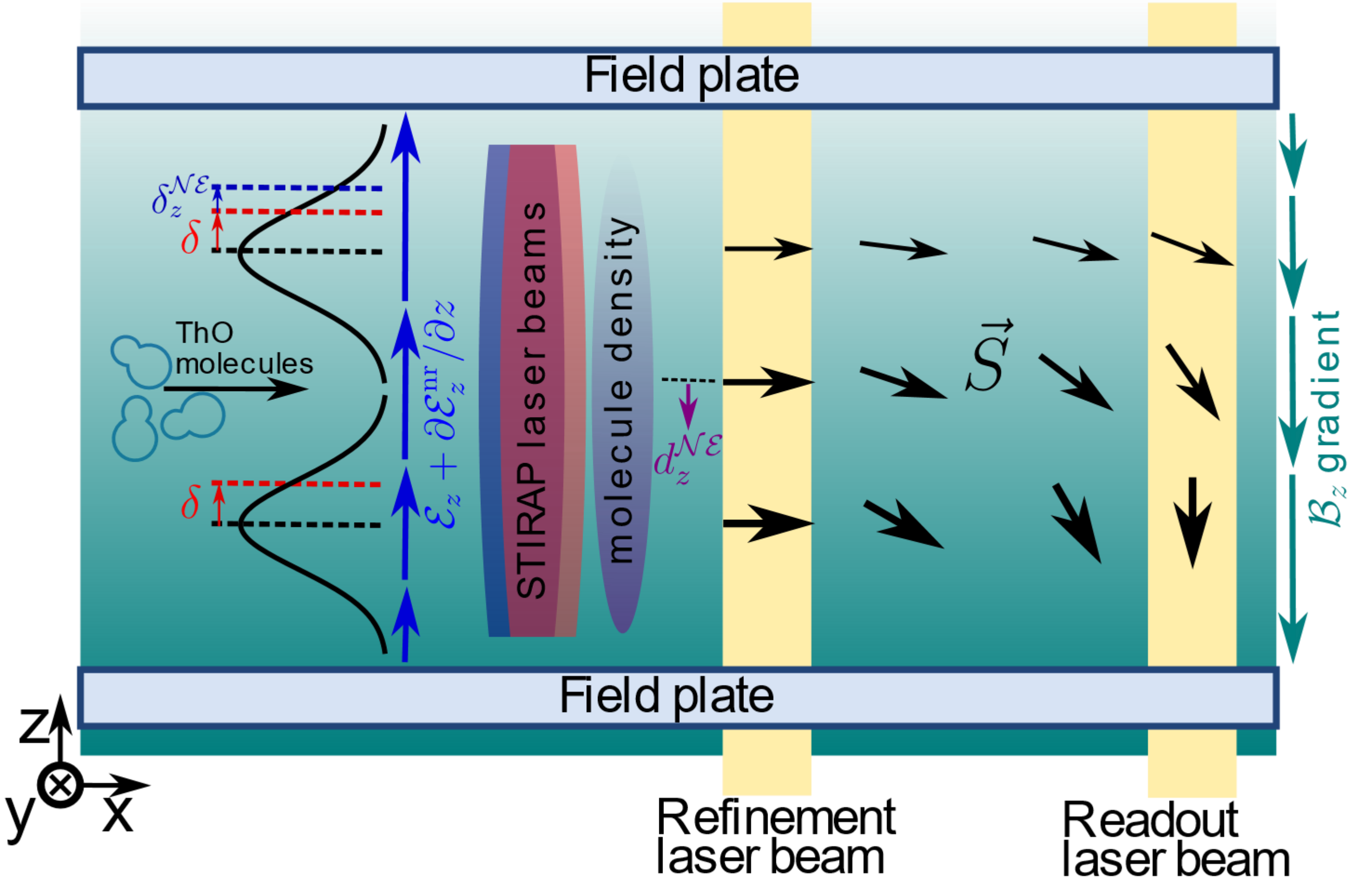
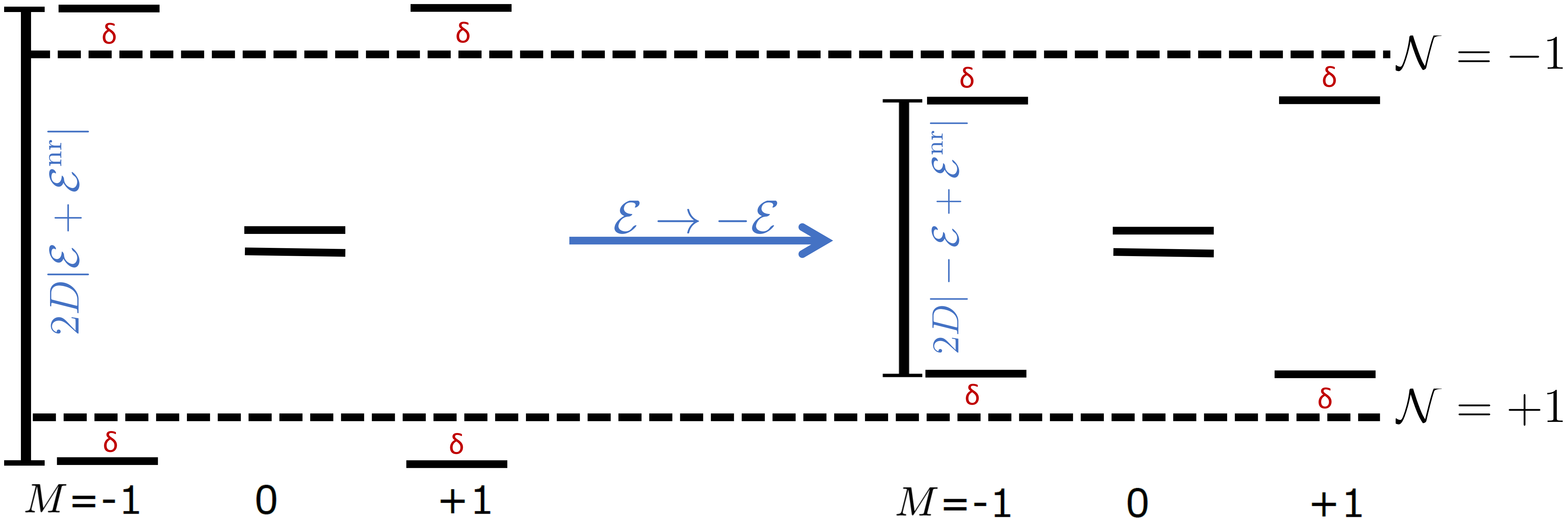
- A translation along z of the "center of mass", dz, of the molecules can then cause a change in measured phase.
- Such a translation can occur due to a z-dependent state preparation efficiency, from a detuning δ_z of the STIRAP resonance.
- For the translation to be EDM-like (NE- correlated), d^{NE}, we need the detuning to also be NE-correlated, δ_z^{NE}. A gradient in the non-reversing electric field dE^{nr}/dz causes such δ_z^{NE}.

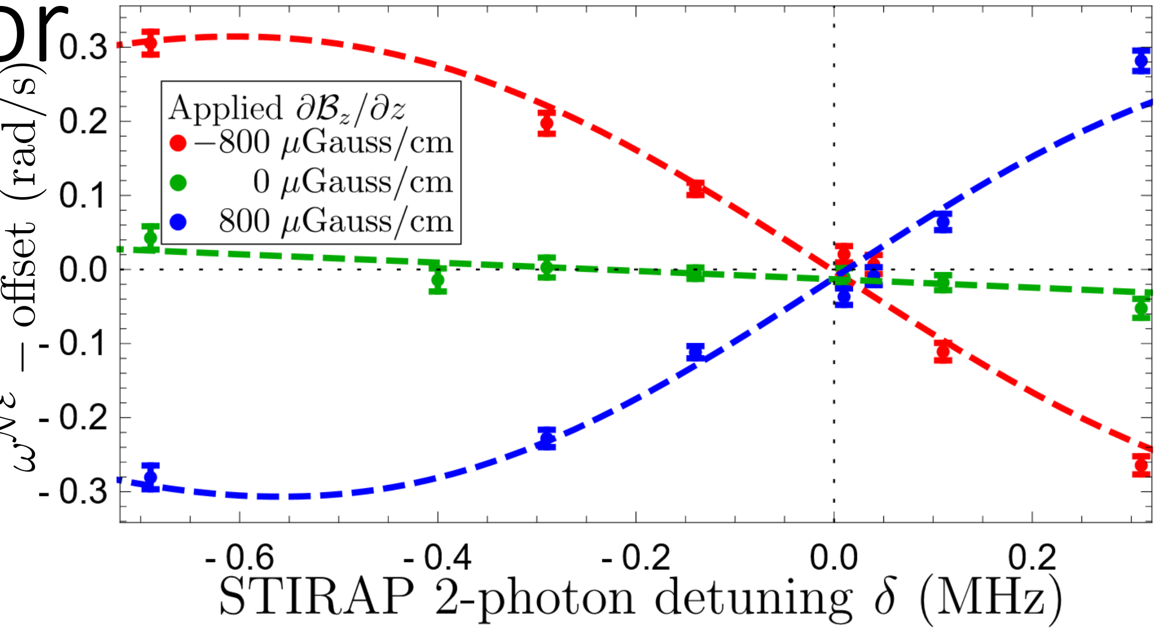


Non-reversing E-field, E^{nr}, causes δ^{NE}



Confirm, minimize, monitor

- Confirm, by looking at dependence on δ.



Confirm, minimize, monitor

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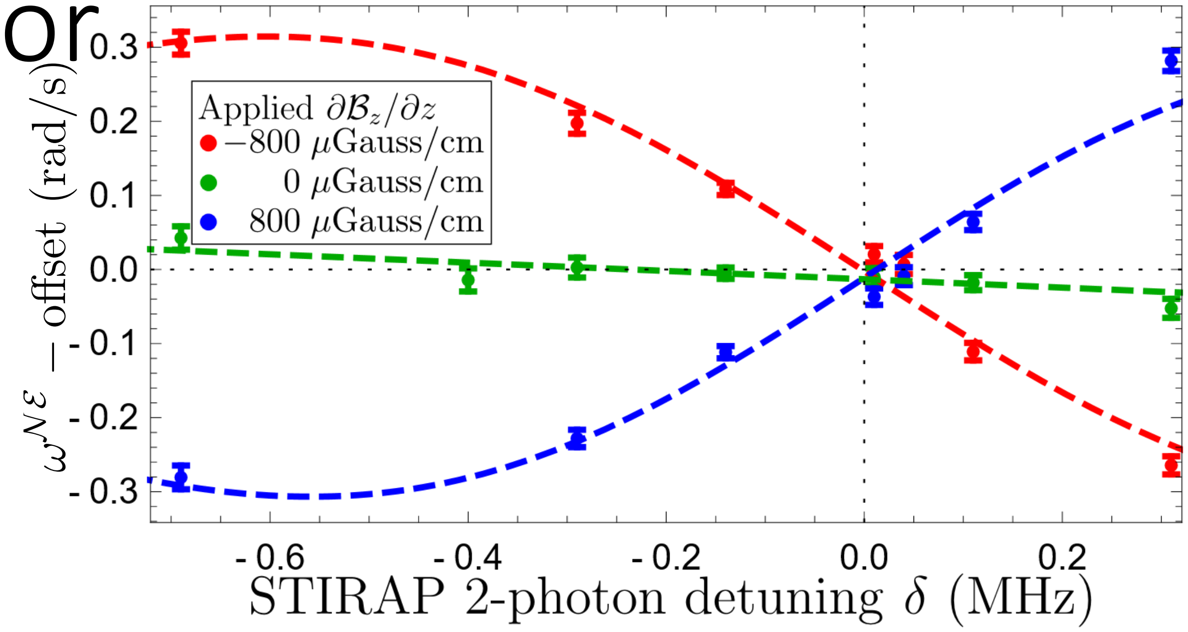
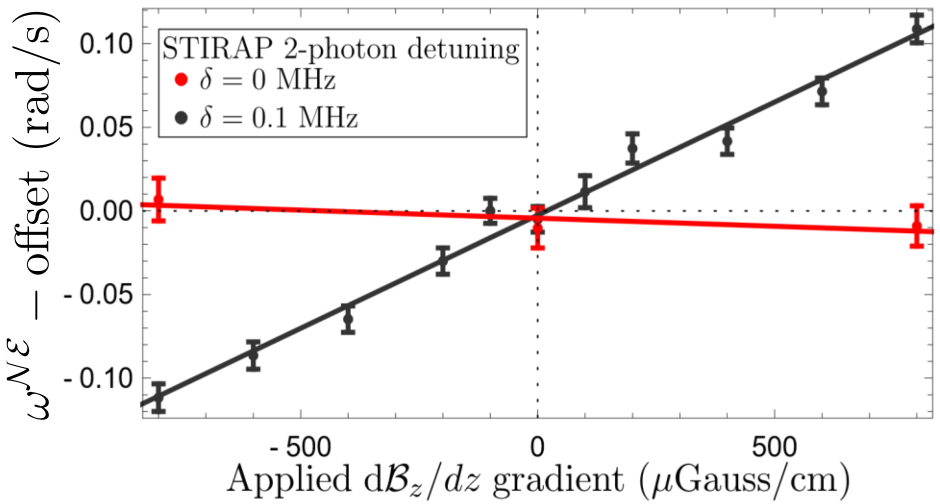
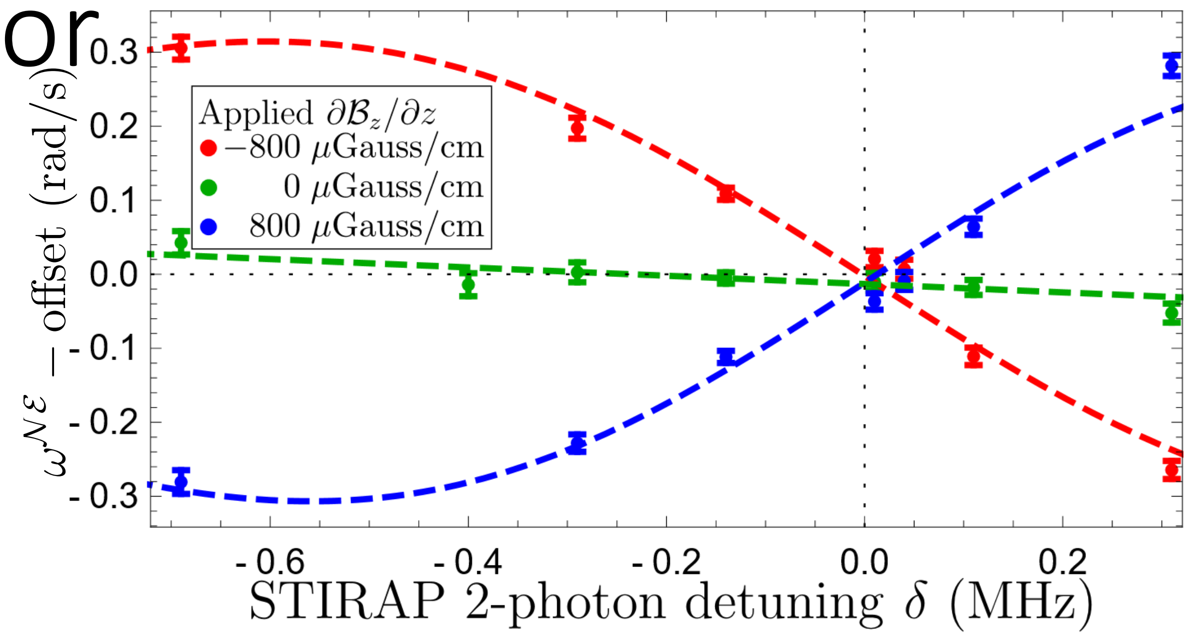
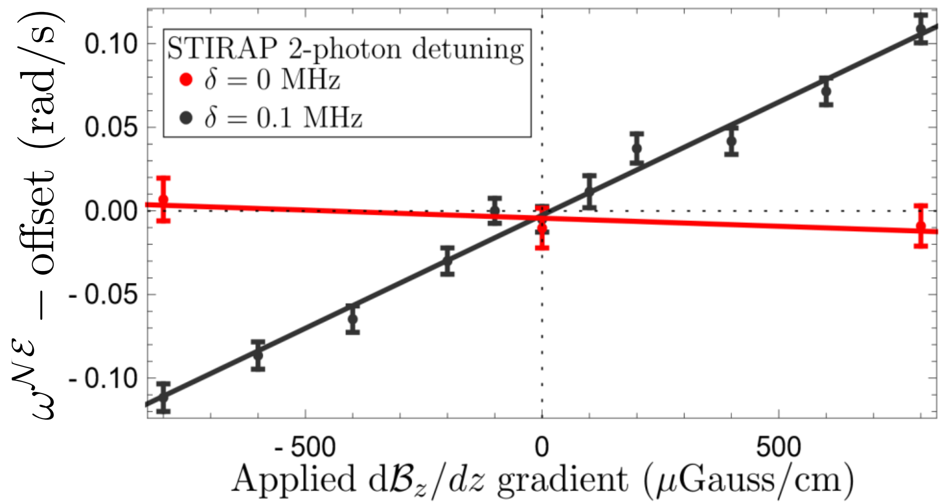


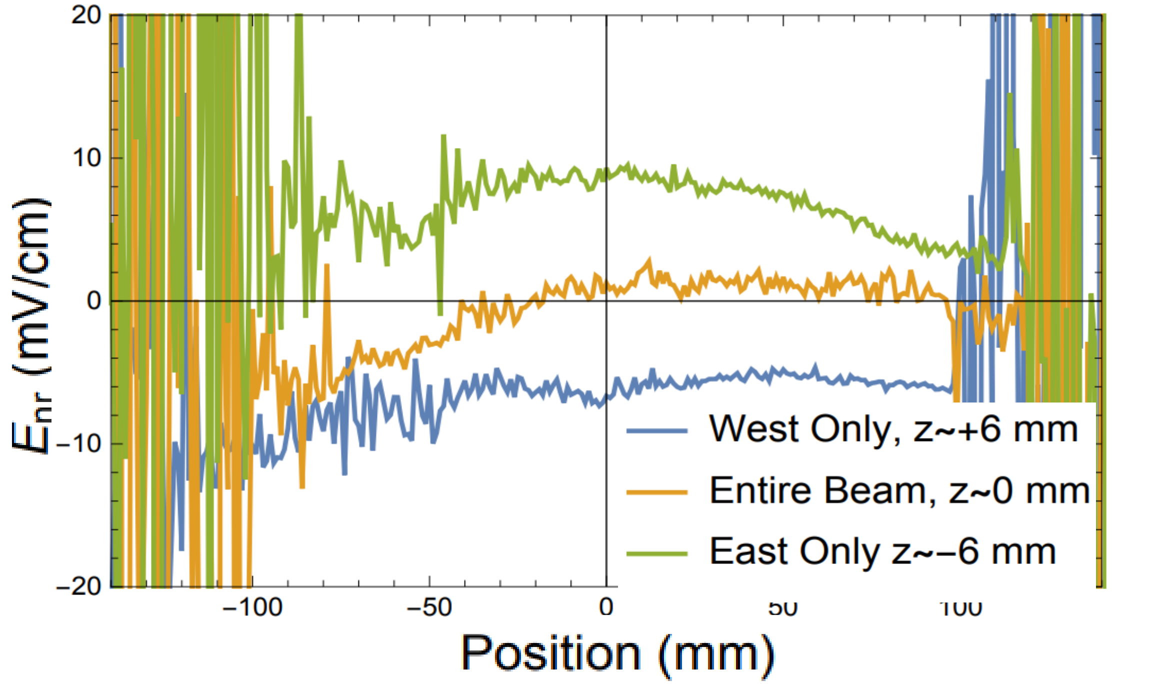


Confirm, minimize, monitor

- Confirm, by looking at dependence on δ.
- Minimize, by tuning and carefully controlling δ=0.
- Measure the size of the imperfections, such as the E^{nr} gradient.
- “Keep an eye” on slope, imperfections during the ACME dataset

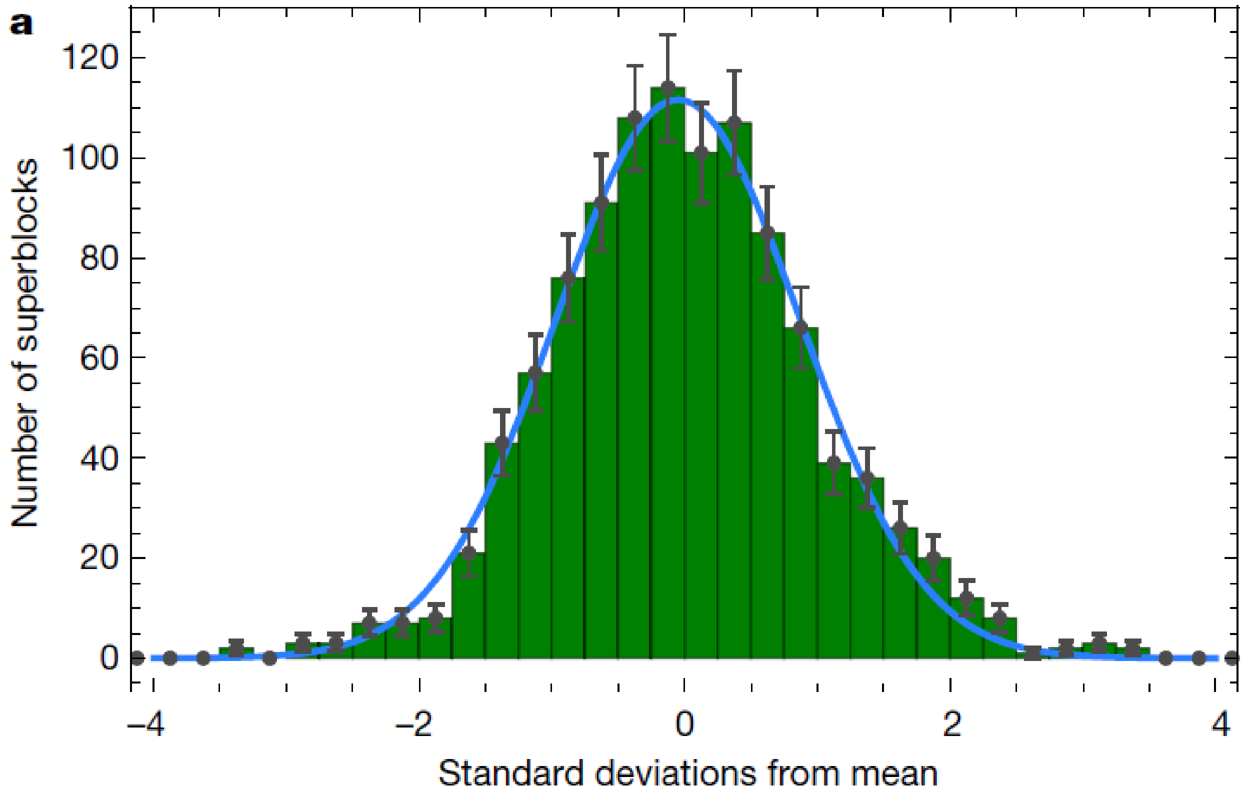






ACME II Dataset

- 2 months of data, ~45 days, 350 hours of EDM, 150 hours of systematic monitoring.
- Bootstrap M-estimator analysis to account for more points in the tails.



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- ACME II uncertainty a factor of 12 smaller than ACME I.

Parameter	Shift	Uncertainty
$\mathcal{E}^{\rm nr}$ correction	-56	140
$\lvert\mathcal{C}\rvert^{\mathcal{NE}}$ and $\lvert\mathcal{C}\rvert^{\mathcal{NEB}}$ corrections	77	125
$\partial\mathcal{B}_z/\partial z$ and $\partial\mathcal{B}_z/\partial y$ corrections	7	59
$\omega_{\rm ST}^{\mathcal{NE}}$ correction	0	1
$\phi^{\mathcal{E}}$-correction	1	1
Other $\mathcal{B}$-field gradients total (4)		134
$P_{\rm ref}^{\mathcal{NE}}$		109
Non-Reversing $\mathcal{B}$-field ($\mathcal{B}_z^{\rm nr}$)		106
Transverse $\mathcal{B}$-fields ($\mathcal{B}_x^{\rm nr}, \mathcal{B}_y^{\rm nr}$)		92
Refinement/readout laser detunings		76
$\tilde{\mathcal{N}}$-correlated detunings		48
Total Systematic	29	310
Statistical		373
Total Uncertainty		486

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- **ACME II blinded result:**

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$\tilde{\mathcal{N}}$-correlated detunings		48
Total Systematic	29	310
Statistical		373
Total Uncertainty		486

$$d_e = (\_\_ \pm 3.1_{\rm stat} \pm 2.6_{\rm syst}) \times 10^{-30}\ e\cdot{\rm cm}$$

ACME II Dataset

- 2 months of data, ~45 days, 350 hours of EDM, 150 hours of systematic monitoring.
- Bootstrap M-estimator analysis to account for more points in the tails.
- ACME II uncertainty a factor of 12 smaller than ACME I.

Parameter	Shift	Uncertainty
$\mathcal{E}^{\mathrm{nr}}$ correction	−56	140
$\lvert\mathcal{C}\rvert^{\mathcal{NE}}$ and $\lvert\mathcal{C}\rvert^{\mathcal{NEB}}$ corrections	77	125
$\partial\mathcal{B}_z/\partial z$ and $\partial\mathcal{B}_z/\partial y$ corrections	7	59
$\omega_{\mathrm{ST}}^{\mathcal{NE}}$ correction	0	1
$\phi^{\mathcal{E}}$-correction	1	1
Other $\mathcal{B}$-field gradients total (4)		134
$P_{\mathrm{ref}}^{\mathcal{NE}}$		109
Non-Reversing $\mathcal{B}$-field ($\mathcal{B}_z^{\mathrm{nr}}$)		106
Transverse $\mathcal{B}$-fields ($\mathcal{B}_x^{\mathrm{nr}}, \mathcal{B}_y^{\mathrm{nr}}$)		92
Refinement/readout laser detunings		76
$\tilde{\mathcal{N}}$-correlated detunings		48
Total Systematic	29	310
Statistical		373
Total Uncertainty		486

- **ACME II result:**

$$d_e = (4.3 \pm 3.1_{\mathrm{stat}} \pm 2.6_{\mathrm{syst}}) \times 10^{-30}\ e \cdot \mathrm{cm}$$

ACME II Dataset

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- Bootstrap M-estimator analysis to account for more points in the tails.
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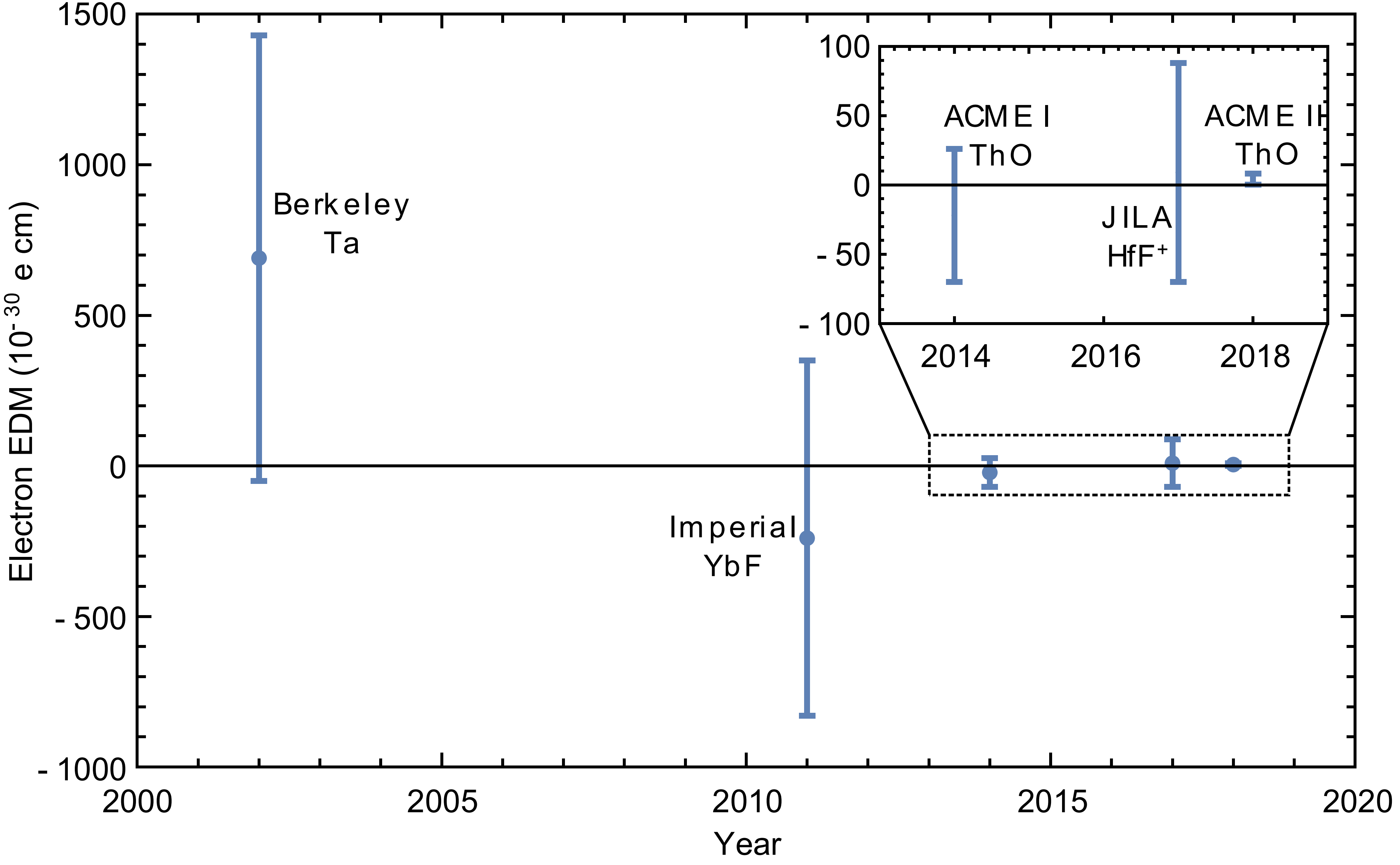
Total Systematic	29	310
Statistical		373
Total Uncertainty		486

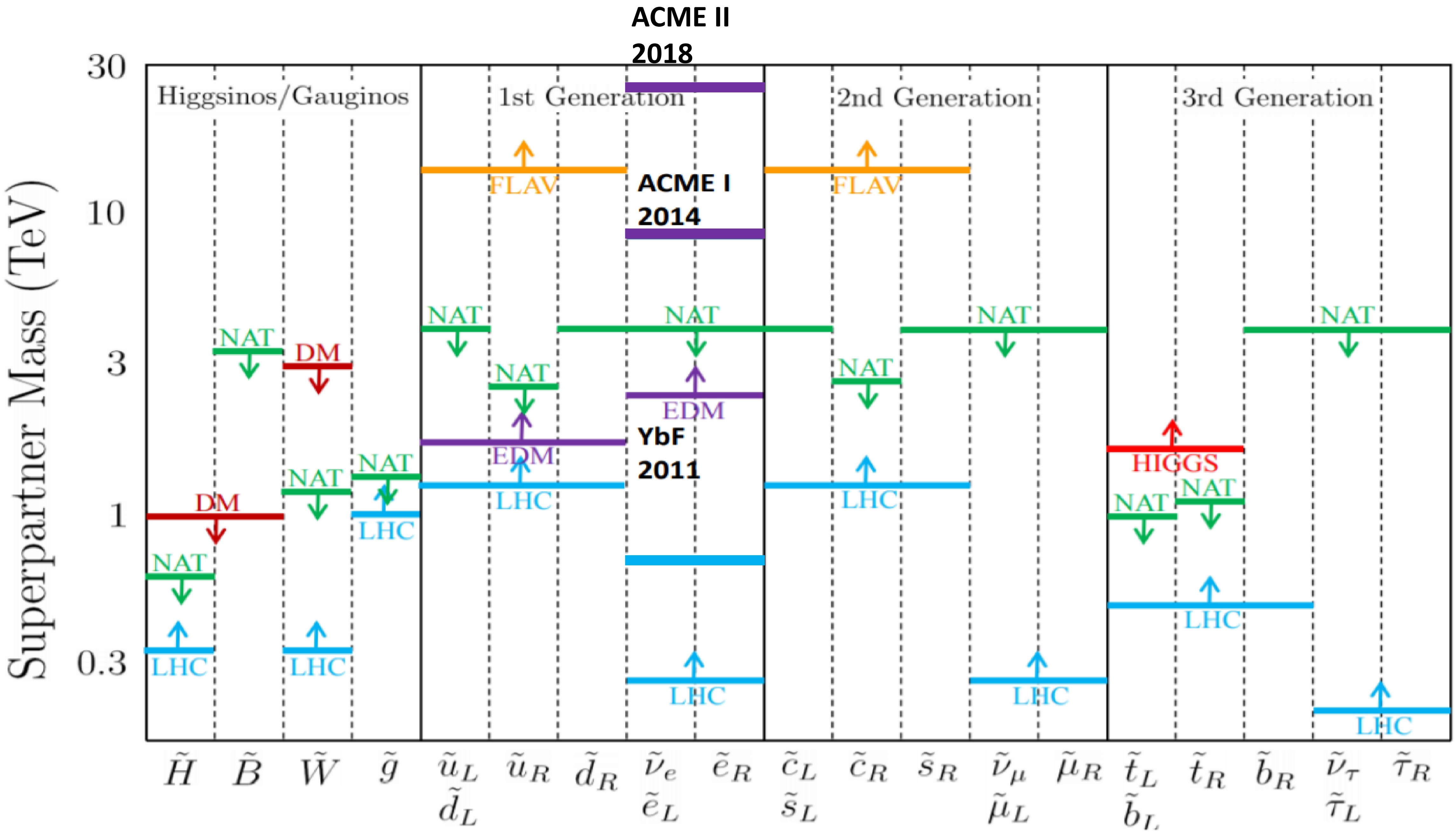
- **ACME II result:**

$$d_e = (4.3 \pm 3.1_{\rm stat} \pm 2.6_{\rm syst}) \times 10^{-30}\ e \cdot {\rm cm}$$

$$|d_e| < 1.1 \times 10^{-29}\ {\rm e{\cdot}cm}\ (90\%\ \text{confidence interval})$$

Electron EDM progress in this millennia

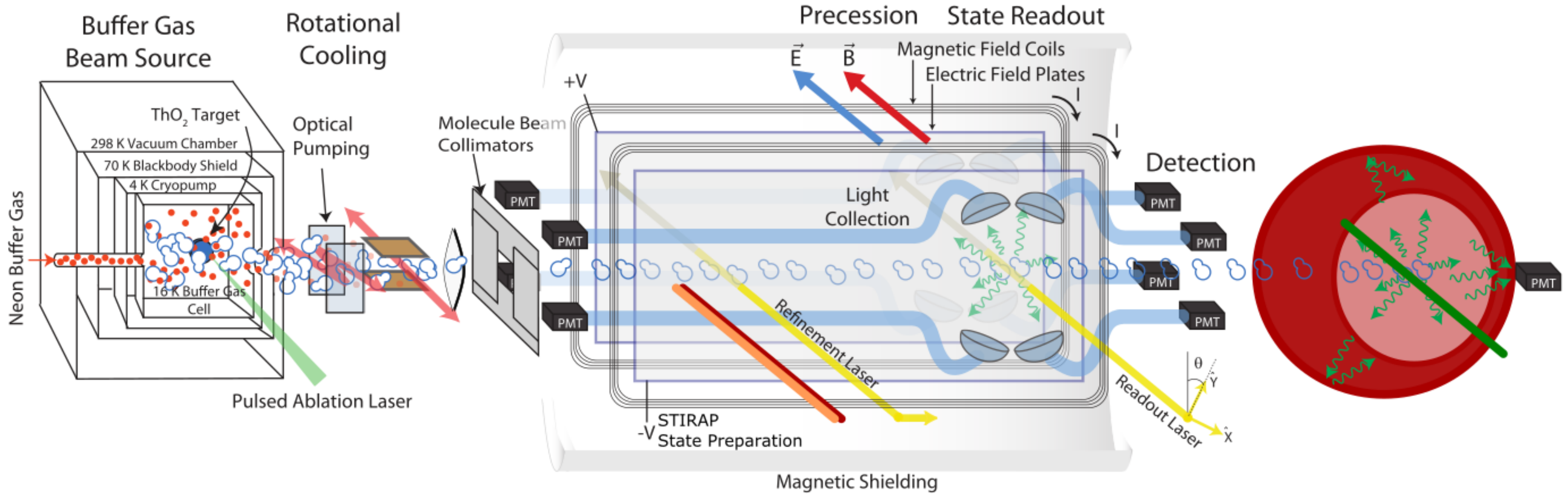




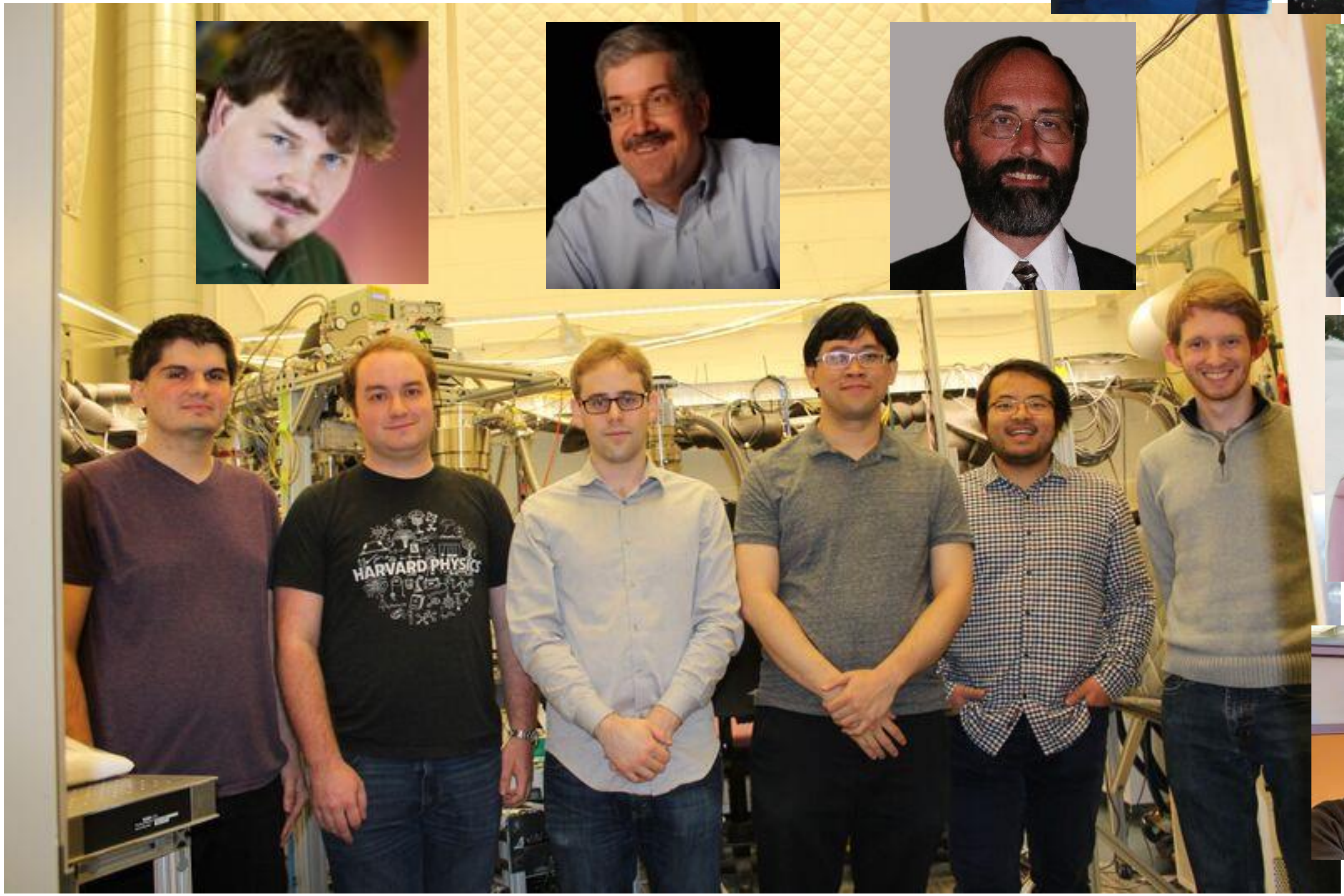
Feng, Naturalness and the Status of Supersymmetry. Annual Review of Nuclear and Particle Science (2013)

ACME III

- Progress underway for more ACME technique upgrades.
- Already understood and suppressed source of excess noise in ACME II dataset, which corresponds to factor of ~3 in signal (~1.7 in EDM sensitivity).
- Electrostatic/magnetic lens could increase molecular flux by up to factor of x10.
- Currently detecting 5% of molecules. Optical cycling could give us 20x photons per molecule, which would make us molecule shot-noise limited.



ACME Collaboration



PI's (left to right)

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